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Sven Odén
1888–1934

On January 16, 1934, Professor Sven Odén died, at the early age of 46. He was professor of chemistry at the Royal College of Technology in Stockholm, and in 1925 became chief of the Chemistry Department of the Central Institute for Agricultural Research, Experimentalfältet, Stockholm, Sweden.

Professor Odén's scientific activities were largely concerned with the sphere of colloid chemistry and its application to the science of the soil. His doctor's dissertation, "Der Kolloide Schwefel," is of considerable theoretical value. The method which he developed for following the rate of sedimentation in soil silting, using an automatically registering balance then calculating the frequency of the various sizes of the particles, is also generally known and highly valued. His contributions in the field of colloid chemistry must be considered of great and lasting importance. In his more recent investigations in the field of soil science, he paid special attention to the study of the acidity of the soil and its lime requirements, in which the electrodialysis method was extensively used and which, with the assistance of his staff, was technically perfected. Among other spheres of applied chemistry in which Odén exhibited his untiring genius for research may be mentioned his investigations on the chemistry of peat, cement, and concrete. His monograph, "Die Huminsäuren," presents a complete bibliography of the subject of the chemistry of the ill-defined and highly complicated group of humus compounds and an attempt to determine their chemical nature. In the field of plant physiology, the effect of light on the development of plants received Odén's attention; he also took considerable interest in practical experiments on the heating of soil by means of electricity and on the growth of plants by means of electric light.

Professor Odén's versatile gifts for research made him stand out as one of the leading personalities in modern agricultural research, from whom there was still much to be expected, and his untimely death is a great loss, particularly for his Scandinavian colleagues and friends.

H. Lundegårdh.

THE CAUSE OF DECREASED NODULE FORMATION ON LEGUMES SUPPLIED WITH ABUNDANT COMBINED NITROGEN

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It has been shown repeatedly (1, 2, 4, 7, 23, 26) that the addition of rather large quantities of nitrates or other readily available nitrogenous salts will either prevent or greatly decrease nodule formation and nitrogen fixation on legume seedlings, depending upon the quantities added and conditions of growth. Under winter greenhouse conditions, where light is deficient and plant growth is slow, very small additions of nitrogen are sufficient to stop all nodule formation, while in the summer much larger rates of application are required to cause an appreciable effect. Giöbel and others have emphasized this point. It has also been proved by many workers, for example Giöbel, Prucha (16), and Hopkins, Wilson, and Peterson, that large applications of nitrogen do not prevent the entrance of the bacteria into the roots nor do they prevent the initiation of nodule formation in many cases. Such nodules, which may become of barely macroscopic size, practically always fail to develop further and may soon disappear if the soluble nitrogen supply continues abundant. Giöbel has also shown that if comparatively small quantities of soluble nitrogenous salts are added at regular intervals to the medium in which legumes are growing, nodulation will be depressed just the same as if added all at once. Furthermore, it was shown as early as 1900 by Hiltner (5) and since then by many others that if nitrates sufficient to stop nodule formation are supplied to a rather young plant, nodules may appear later in the life of the plant after the concentration of nitrate has been sufficiently depleted and that, too, without additional inoculation.

SUGGESTED EXPLANATIONS FOR THE DEPRESSING EFFECT OF AVAILABLE NITROGEN ON NODULE FORMATION

In an attempt to account for the harmful effect of nitrates or other readily available sources of nitrogen on nodulation a variety of findings and suggestions have been offered by various investigators. Probably the most important of these are as follows:

[1] The writers wish to thank Dr. Dean Burk for many helpful suggestions given while this manuscript was being prepared and Messrs. H. J. Morris and Sam R. Hoover for assistance in carrying out some of the experimental work.

1. Hiltner (5) believed that nitrates strengthen the host plant and make it capable of resisting bacterial entrance. The whole phenomenon was explained on the basis of his immunity theory.

This idea is entirely theoretical and there is little or no evidence in support of it. Bacteria can enter roots even in the presence of excess nitrate and may initiate nodule formation.

2. The inoculating power of bacteria may be injured by the presence of nitrates.

Many of the earlier workers held this view, but it is now universally considered as not being in accord with the facts.

3. Giöbel suggested that the plant can absorb and use nitrates much more quickly than the complex organic nitrogenous compounds fixed in the nodule, allowing the latter to accumulate and stop growth.

This is not a fundamental explanation for the phenomenon because where nitrates prevent nodule formation there is no nitrogen fixation and, of course, no accumulation of end products. A somewhat similar idea to that of Giöbel's, commonly expressed, is that plants form nodules and fix nitrogen only in case they need it, but this is also no explanation for the cause of nodule failure.

4. Laurent (9) suggested that the nitrate reacts with the plant sap to form some compound toxic to bacteria.

Nitrate certainly does combine with the plant carbohydrates to form proteins as the end products, but these are not toxic to the bacteria. There is no evidence that toxic compounds are formed, at least none that are not also formed when atmospheric nitrogen is the source of this element.

5. Wilson (28) concluded from his divided root experiment that the effect of nitrates is local in character.

Present information partially supports this conclusion but, as will be pointed out later, the nutrition of the entire plant is involved. It should be emphasized in this connection that the maximum nitrate concentration which Wilson used was less than twice as great as one which permitted nodule production on both sets of roots. It would be expected in the light of carbohydrate-nitrate relations, to be discussed later, that higher nitrate concentrations (if not toxic) would have prevented nodule formation on both sides of the root system.

6. Strowd found very high concentrations of nitrate in root tissues grown in nitrate solutions and concluded that the concentration was sufficiently high to hinder the growth of the bacteria in the tissues and hence to stop nodule formation. Marchall (11) in earlier work came to a somewhat similar conclusion, suggesting that nitrates produce an osmotic state which hinders the development of the bacteria.

Giöbel considered this idea at some length, and his view that Strowd's data do not justify his conclusions is undoubtedly correct. Nodule bacteria seem to be able to tolerate at least as high a concentration of nitrates as can legume plants.

7. Strowd also considered the possibility that the toxic action of nitrates may be due to their effect upon the hydrogen-ion concentration of the sap. Experimentally he observed little effect on the acidity and, hence, discarded the idea.

8. Mazé (13) suggested that the bacteria find sufficient nutrition outside the plant and do not enter it.

The answer to this suggestion is the finding of Giöbel, Prucha, and others that nitrate applications do not prevent the entrance of the root nodule bacteria. Furthermore, Strowd makes the pertinent remark that if Mazé's theory is correct there should be no dimunition in size of nodules in the presence of moderate amounts of nitrates; there should be either well-developed nodules or none at all.

9. Mazé in 1898 also suggested that the nitrate reacts with the sugar in the plant, leaving little for the bacteria. He believed that nitrogenous material is not harmful to bacterial development but that in the presence of excess nitrates the nitrogen combines with the carbohydrates formed in the leaves and little carbohydrate reaches the roots. Consequently, the root hairs do not lose any by diffusion, the bacteria in the soil are not attracted, and few,

if any, nodules form. These few remain small because they are deprived of carbohydrates. Weber's (26) recent studies led him to a conclusion only slightly different from that of Mazé, namely, that in the presence of excess nitrates there is no adequate carbohydrate nutrition for the bacteria and that the carbon-nitrogen ratio is not maintained sufficiently wide to permit the bacteria to carry on active nitrogen fixation.

In the opinion of the writers the carbohydrate deficiency idea is the only suggested explanation that is in agreement with the known facts, although neither Mazé nor Weber presented it in the true light. Mazé stressed the necessity for carbohydrate for bacterial entrance and growth, whereas Weber emphasized the need for a wide carbon-nitrogen ratio for bacterial growth and nitrogen fixation. These are not the primary functions of the carbohydrate. It is of much greater importance that a sufficient supply be available for the growth of the root tissue; otherwise it is impossible for the nodule tissue to form.

EFFECT OF SOLUBLE NITROGENOUS SALTS ON THE CARBOHYDRATE CONTENT OF ROOTS AND UPON ROOT GROWTH

Photosynthesis, of course, normally supplies the carbohydrates needed for respiration and growth of legume plants and for the bacteria living in the nodule. If plants (nonlegumes or nodule-free legumes) are grown in the presence of an insufficient nitrogen supply it is well known that they will accumulate carbohydrates, mostly as starch deposited in many places among the plant tissues. On the other hand, in the presence of an abundance of available combined nitrogen a rapid growth occurs, and the carbohydrate content in this case is kept low or is decreased if originally high. Growth occurs up to the point where carbohydrate becomes the limiting factor.

An extremely important point not heretofore stressed in this connection, which is the key to the whole discussion, is the fact that if an abundant supply of soluble nitrogen is given to a plant (legume or nonlegume) a greatly increased top growth and a comparatively small root growth result. This failure of roots to grow appreciably is due chiefly to lack of carbohydrates in the roots. There is such a mass of evidence in support of these ideas that it seems entirely unnecessary to present new experimental evidence. Miller (14) has discussed many phases of the subject at some length. The papers of Kraus and Kraybill (8), Gericke (3), Starring (22), Reid (17, 18, 19, 20, 21), and Müller (15), for example, show the importance of carbohydrates in root development and the unfavorable effect of nitrogen.

As a result of studies with nonlegumes, particularly barley and corn, Turner (25) concluded that "the increased ratio of tops to roots which results from increasing the amount of nitrate in the solution may be explained on the basis of increased use of carbohydrate in the tops because the greater nitrogen supply makes for greater growth. This results in a decrease in the supply of carbohydrate for the roots, which may bring about an absolute or a relative reduction of root growth." His experiments showed that nitrates actually increase (not

decrease) root growth where grown in pure culture with an adequate sugar supply.

The results of Fred and Graul (2), reported in part in table 1, together with calculations by the writers of the top-root ratios, bear directly upon the subject under discussion. In the case of alfalfa receiving only a little or no combined nitrogen the top-root ratio was about 1.0, whereas at a nitrate concentration

TABLE 1

Effect of nitrates on the relative growths of the tops and roots of alfalfa and vetch

NITRATE N ADDED PER 100 CC. OF SOLUTION	DRY WEIGHTS		TOP-ROOT RATIO	NODULE OCCURRENCE
	Tops	Roots		
mgm.	*gm.*	*gm.*		
Alfalfa, uninoculated				
0	0.1	0.3	0.33	None
1	0.8	0.8	1.00	None
5	3.8	3.0	1.27	None
10	5.5	2.8	1.96	None
15	3.7	1.5	2.47	None
Alfalfa, inoculated				
0	0.3	0.2	1.50	Numerous
1	1.4	1.5	0.93	Numerous
5	3.9	2.5	1.56	Numerous
10	4.9	2.3	2.13	Few
15	5.6	2.5	2.24	None
Vetch, uninoculated				
0	0.6	1.8	0.33	None
1	3.4	2.0	1.70	One
5	5.0	4.2	1.19	None
10	7.4	2.5	2.96	None
15	3.9	1.2	3.25	None
Vetch, inoculated				
0	4.0	2.4	1.67	Numerous
1	4.9	6.7	0.73	Numerous
5	5.9	3.5	1.69	Few
10	7.4	2.5	2.96	Very few
15	4.0	1.5	2.67	None

sufficient to stop all nodulation the ratio was on the average 2.35. The figures for vetch showed a corresponding increase in top-root ratio from approximately 1.2 with little nitrogen to 3.0 where the nitrate application stopped nodule formation. With smaller nitrate applications the ratios were intermediate and nodule formation was an inverse function of the quantity of nitrogen added.

Welton and Morris (27) reported somewhat similar data for soybeans, the total weight of the roots of plants grown in a heavily manured soil being actu-

ally slightly less than on plants grown on a poor sand even though the weight of the tops was about 64 per cent greater in the former case. The numbers of nodules in the poor and rich soils were 379 and 62, respectively. Prucha (16) calls especial attention to the much better development of the root system of the Canada field pea grown in a nitrate-free solution in contrast to that grown in nitrate solutions.

It seems clear that nodules are produced only where root growth as compared with top growth is reasonably good.

A detailed consideration of why an abundant nitrate supply tends to reduce root sugar and in turn cause a wide top-root ratio scarcely falls within the realm of this paper. In fact, plant physiologists are not in entire agreement as to the correct explanation of the facts. Suffice it to say that it has been shown, at least in the case of the cotton plant that a sugar concentration gradient commonly exists between the leaves and the stems and roots. Furthermore, under conditions of abundant nitrogen supply carbohydrate is ordinarily the limiting factor in plant growth and, since all plant cells are consuming it, those farthest from the supply would be expected to receive the least and make the poorest growth, as Turner pointed out.

With this background of facts is it surprising that the addition of available nitrogen may decrease or stop nodule formation? Under exactly the same conditions the roots of the same plants make a negligible growth because of an insufficient energy supply. Nodule tissue may be considered, so far as this discussion is concerned, as root tissue slightly modified, and if the energy available is insufficient for root growth in the presence of nitrates it is obviously inadequate for the growth of nodules, located on the roots. With moderate nitrate applications some nodule tissue may form but under the same conditions some root tissue may likewise develop, the extent of development of both depending upon the carbohydrate supply, assuming that other growth conditions are satisfactory. It is an invariable rule that *nodules grow only where a sufficient supply of carbohydrates is present to allow at least a moderate root growth.*

When the question of why nodules fail to form in the presence of nitrates was first given consideration in this laboratory the advisability of making chemical analyses for sugars and starch in legume roots was considered, but the idea was set aside, chiefly for the reason that it was not believed that this method of attack would lead to conclusive results or furnish much new information. Although the total quantity of carbohydrates which reaches the roots in a given length of time may be greatly decreased by nitrogen additions the actual percentage of sugars in the roots of a plant growing in normal light will not necessarily be extremely low. Furthermore, any attempt to determine the effect of nitrates on root carbohydrates is greatly handicapped by the fact that even under reasonably constant growth conditions the normal diurnal and day to day variations in carbohydrates, especially of reducing sugars, may be rather large. Since we are dealing with a living system involving carbohydrate syn-

thesis on the one hand, and its utilization on the other, the quantity of readily available carbohydrates present at any one time represents only a small percentage of the total. This small percentage is, of course, subject to marked variations if either the rate of photosynthesis or utilization changes. While nitrate additions would undoubtedly tend to lower the carbohydrate content to some extent, an accurate determination of the nitrate effect, apart from other variations, would probably not be easy. The analytical difficulties are further intensified by the fact that the plant can easily change reducing sugars to starch or starch to sugars, as needed and where needed.

The data of Strowd, reported in table 2, are of interest in this connection. Reference should be made to his original paper for the experimental details.

It will be observed that Strowd found that at nitrate concentrations sufficient to stop nodule formation the concentration of reducing sugars in the roots was approximately half that of the check. Since the plant juice, even in the presence of nitrates, contained a fair concentration of reducing sugars

TABLE 2

Effect of nitrates in sand on the reducing sugar content of the root juice of soybeans

NITRATE N ADDED TO 100 GM. SAND	FIRST EXPERIMENT (AFTERNOON HARVEST)		SECOND EXPERIMENT (MORNING HARVEST)	
	Nodules	Reducing sugar*	Nodules	Reducing sugar*
mgm.		*mgm.*		*mgm.*
0	Large, abundant	342	Large	220.0
2.5	Small, few	421	.....	.....
5.0	None	187	Very small	107.4
10.0	None	168	None	75.8
20.0	No germination			

* Calculated as dextrose per 100 cc. of root juice.

Strowd was apparently not inclined to attach much importance to the idea that lack of carbohydrates was responsible for lack of nodules. He did not, however, entirely set aside the carbohydrate theory, concluding that "before any definite conclusion can be drawn in this regard, it will be desirable to determine whether or not the addition of sugar to the soil counteracts the depressing effect of nitrate." Giöbel also rejected the carbohydrate idea on the basis of Strowd's findings.

Contrary to the views of Strowd and Giöbel the writers consider that Strowd's data offer some evidence that nodules fail because of insufficient carbohydrate; at any rate the results are not contrary to that idea. The fact that the soybean roots contained reducing sugar is no proof that the root carbohydrate supply was adequate for the growth either of nodule or root tissue. There is certainly no reason to expect sugars to be absent under such experimental conditions, but rather they should be merely decreased as Strowd actually found in all cases except with the smallest rate of application of nitrate. Sugar must be present

in plant tissues continually to meet the needs for respiration or else the plant cells will soon die. After these respiration needs are met then if sufficient carbohydrate is present growth can take place, first largely in the leaves and stems and then in the roots. Not until the supply is adequate for a fair amount of root growth will nodule development occur. Apparently a slightly higher energy level is needed for nodule tissue growth than for root tissue growth, thus accounting for the fact that in the presence of an abundance of available nitrogen some root development may occur without nodules forming. The physical difficulty of transporting sugars into a nodule may be an adequate explanation, but it is also highly probable that the total energy requirements in the nodule for the respiration and growth of the bacteria and host tissue, for nitrogen fixation, and for protein synthesis, are greater per unit dry weight than the energy needs for a corresponding weight of root tissue.

We may summarize by saying that under constant conditions of growth the plant tends to establish a carbohydrate equilibrium. A change in photosynthetic activity or in the supply of available nitrogen may cause some change in the carbohydrate concentration, but except under rather extreme conditions ordinarily the variation is not over a wide range except temporarily. If the rate of photosynthesis is increased, in the presence of a normal nitrogen supply, then the carbohydrate concentration may also increase somewhat, but *it is the amount of plant growth that increases most and not the carbohydrate concentration.* On the other hand, if photosynthesis is decreased to the point where the supply is inadequate for respiration then of course the available carbohydrate concentration may drop to approximately zero. If the plants are maintained in normal light and the available nitrogen supply is made to vary, then an abundance of nitrogen causes a marked increase in top growth and a comparatively small root growth. We would expect some drop in sugar concentration in the roots, as Strowd found, but there should still be a fair concentration in view of the fact that such roots are still respiring and making some growth. It should always be borne in mind that this paper deals specifically with the latter set of conditions—normal light and high available nitrogen.

EXPERIMENTS TO DETERMINE THE EFFECT OF SUCROSE AND OF NITRATE ON NODULE FORMATION ON LEGUMES

The foregoing review and discussion suggest that a simple method of obtaining experimental data on the subject would be to add varying amounts of sugar and nitrates to the substratum in which legumes are growing and note the effect on nodule production. It is a well-established fact that the addition of sugar to plant roots usually causes a marked increase in root development and under some conditions also in nodule development, but very little is known about the combined effect of sugar and nitrates. Such experiments, alone, would never conclusively answer the question under consideration but the data should add an important link to the long chain of evidence already accumulated on the subject. Some work of this type is reported in the following.

The experimental method adopted was to determine the effect of sugar and of nitrate used singly and in combination on nodule formation on seedlings during short experimental periods. The cultures were not continued for longer periods because of the practical impossibility in sand culture of maintaining a constant sugar concentration or of preventing decomposition of the sugar by the nodule organisms, with the consequent presence in the substratum of various unknown end products. The use of solution cultures would be subject to the objection that under such conditions nodules do not develop normally and nitrogen fixation is usually slight.

Two preliminary experiments were made without success. In the first experiment sucrose and sodium nitrate were added to unsterilized sand, but fungi attacked the germinating seeds, especially where both nitrate and sucrose were added, to such an extent as to ruin the experiment. In another experiment sterile alfalfa seeds were planted in sterilized sand in bottles, fitted with cotton plugs, and kept under artificial lights. The temperature was excessive, and the germination irregular in the presence of sucrose, hence the experiment was soon discontinued. Two successful experiments, reported here as experiments 1 and 2, are described in detail in the following.

Experiment 1. In this experiment 4,200-gm. portions of washed nitrogen-free sand were placed in glazed earthenware jars and moistened with 675 cc. of Thornton's (24) nitrogen-free culture solution. After being covered with paper the pots were sterilized, and 105 sterile alfalfa seeds were placed on top of the sand and covered with 300 gm. of sterile dry sand. The required amounts of sterile sucrose and nitrate solutions were added, likewise 10 cc. of a heavy inoculum of a young culture of alfalfa bacteria, and sufficient distilled water to bring up to weight. The following day the pots were placed in a special artificially lighted apparatus, to be described elsewhere (10), which has given excellent results in the growing of plants. The light source was ten 500-watt Mazda lamps and one glass mercury vapor lamp per total bench area of 25 square feet, giving a light intensity of about 2,000 foot candles. The temperature of the sand in the pots was maintained between 20 and 27°C. by means of a water bath. Aseptic precautions were taken in starting the experiments, but the pots were exposed to the air after planting and no further precautions were taken against contaminations other than to avoid unnecessary handling. The work was done in a basement room which was very free from dust. No difficulty was experienced from contaminating organisms either in this experiment or in experiment 2, although undoubtedly the sand was not kept entirely free from foreign organisms. The average number of seeds per pot which germinated was about 85 out of a total of the 105 seeds planted. The extremely weak and abnormal plants, which on the average amounted to about 12 per pot, were discarded in all cases. The nodule counts, made 7, 8, and 14 days after planting, are recorded in table 3.

It will be observed that the concentration of nitrate used was barely sufficient to retard early nodulation but not to prevent it, and that after 14 days it was

about 76 per cent as good in the presence of nitrates as on the check plants. Sucrose, alone, also markedly retarded the production of nodules on alfalfa, as shown by the first count, but the effect had been largely overcome by the

TABLE 3

Effect of potassium nitrate and sucrose, used singly and in combination, upon nodule production on alfalfa seedlings

	PER CENT OF PLANTS WITH NODULES AFTER			AVERAGE NUMBER OF NODULES PER PLANT AFTER		
	7 days	8 days	14 days	7 days	8 days	14 days
Untreated	58.2	68.0	99.5	1.05	1.68	5.57
Potassium nitrate (20 mgm. N)	28.1	25.6	97.5	0.33	0.33	4.26
Sucrose (1 gm.)	19.6	50.6	94.9	0.25	0.88	4.76
Potassium nitrate (20 mgm. N) plus sucrose (1 gm.)	40.0	74.7	100.0	0.67	1.63	5.72

TABLE 4

Effect of varying concentrations of potassium nitrate and sucrose upon the nodulation of alfalfa seedlings

SUCROSE (GM. PER POT)	POTASSIUM NITRATE (MGM. N PER POT)						
	0	2.5	5	10	20	40	80
0	0.83	0.63	0.23	0.18	0.08	0.05	0.00
	4.52	3.54	4.72	3.71	3.17	1.02	0.34
0.125	1.16	0.59					
	3.42	4.93					
0.25	0.72		0.58				
	2.87		4.26				
0.5	1.17			1.16			0.00
	5.53			6.64			0.27
1.0	1.25				0.37		
	5.29				5.30		
2.0	1.31		0.70			0.38	0.04
	3.56		4.48			4.12	0.51

Upper figures—average number of nodules per plant after 8 days.
Lower figures—same after 12 days.

following day. It is a well-known fact, confirmed by the experiments reported here, that in the presence of added sugars seed germination is frequently retarded and the growth of the young seedlings hindered. Where both sugar and nitrate were added there was some retardation in germination, but to a

lesser extent than with sucrose alone. The nodule counts in this case, made on the seventh day, were higher than where either sugar or nitrate alone was added but slightly less than on the check. The counts made the following day showed that the sugar had entirely overcome the harmful effect of nitrate on nodulation. It is clear, then, that in this experiment even though sucrose, used singly, decreased early nodulation it was nevertheless able to counteract the harmful effect of nitrate where used together with it. This is direct evidence for the idea that lack of available carbohydrates is responsible for decreased nodulation in the presence of soluble nitrogen.

Experiment 2. In the second experiment the methods used were the same as in the first experiment except that varying concentrations of sucrose and nitrate, added singly and in combination, were used. The results are given in table 4.

It will be observed that at the first counting of nodules increasing concentrations of nitrate had decreased nodule production proportionately up to the highest concentration, where no nodules had formed. The various applications of sugar alone, with the exception of one treatment, had increased the number of nodules formed in 8 days. In the previous experiment sugar alone showed a marked retardation of nodulation at the end of 7 days but the effect was nearly overcome by the 8-day period. In this experiment, where counts were not made until the 8-day period, four out of five pots showed more nodules than the check. The combined application of sugar and nitrate usually resulted in the formation of more nodules than where only nitrate was used although in only one out of eight pots was the number of nodules as great as on the check plants at the 8-day period.

The data obtained on the twelfth day show the continued retarding effect of nitrate on nodulation except at the lowest concentrations. Sugar, alone, caused a slight increase in two cases and a decrease in three others. These plants grew more slowly than those in the check pots, showing that sugar under these conditions was somewhat harmful to growth. The use of sugar together with nitrate counteracted the effect of the latter to such an extent that nodule production was approximately the same as on the check plants, except at the largest rate of application of nitrate.

DISCUSSION

The experimental evidence presented here shows that regardless of the fact that sucrose, alone, retarded germination and plant growth it did to a marked extent counteract the harmful effect of nitrates on nodulation. If the retarding effect of sugar had not been so marked it is reasonable to suppose that it would have had an even greater effect in counteracting the nitrate effect. It is also probable that the sucrose entered the roots so slowly under sand culture conditions that the concentration of the sugar in the root sap was not markedly increased and hence produced less effect than would have been observed in solution cultures.

Although the writers consider that their data lend support to the carbohydrate hypothesis, the results do not, of course, prove it but merely serve as an additional bit of the evidence, all of which is apparently in harmony with the idea. It is again desired to emphasize that nodule formation involves the rapid growth of tissue, and in searching for the reason for nodule failure we must find the reason for the failure of root tissues to grow. When conditions are such as to prevent rapid root growth it cannot be expected that nodule development will continue unchecked. Since we know that *an excess of assimilable nitrogen greatly retards root growth as compared with top growth and may even practically stop it temporarily because the carbohydrates are used almost quantitatively in the tops, it is scarcely necessary to look further for an explanation of the failure of nodules to develop on these same roots. The nodule bacteria play an incidental rôle in the phenomenon.*

After this article was ready to be sent to the publishers the recently published paper of Hopkins and Fred (6) came to the attention of the writers. Reference to this article will show that in most respects the conclusions presented agree with those presented here except that emphasis is somewhat differently placed. Hopkins and Fred emphasize the necessity for a sufficient concentration of carbohydrate to permit the bacteria to proliferate and incite nodule formation, whereas we believe that the bacteria play a very secondary rôle and that the carbohydrate is needed mostly for plant tissue development, whether it be nodule tissue or normal root tissue. Experimentally, the initiation of nodule formation alone was considered in this laboratory, whereas at the Wisconsin station more emphasis was placed on the distribution and size of nodules and on the quantity of nitrogen fixed after a long growth period.

SUMMARY

A review of previous work and suggestions, dealing with the cause of the depressing effect of available nitrogen on legume nodule formation, is given.

Calculations made from previously published data show that the top-root ratios of legumes grown with varying amounts of available nitrogen increase with increase in nitrogen supply. Under similar conditions there is a decrease in the quantity of reducing sugars in such roots.

Experiments are reported showing that sucrose, added to sand cultures of alfalfa, tended to overcome the injurious effect of nitrate on nodule formation except at the highest concentration of nitrate used. This beneficial effect of sucrose was observed regardless of the fact that where used alone it retarded germination and early plant growth.

It is believed that the evidence from all the experimental work so far reported proves beyond a reasonable degree of doubt that decreased nodulation in the presence of soluble nitrogenous salts is due to inadequate carbohydrate supply in the roots. The effect on the bacteria themselves plays a very secondary rôle in the phenomenon. Where nitrogen is abundant the carbohydrate synthesized is used for top growth, and little is available for the growth of roots or

nodules. Nodules grow only where enough carbohydrate is present to allow at least a moderate root growth.

REFERENCES

(1) FRED, E. B., BALDWIN, I. L., AND MCCOY, E. 1932 Root nodule bacteria and leguminous plants. *Univ. Wis. Studies Sci.* 5: 1–343.

(2) FRED, E. B., AND GRAUL, E. J. 1916 The effect of soluble nitrogenous salts on nodule formation. *Jour. Amer. Soc. Agron.* 8: 316–328.

(3) GERICKE, W. F. 1922 Certain relations between root development and tillering in wheat: significance in the production of high-protein wheat. *Amer. Jour. Bot.* 9: 366–369.

(4) GIÖBEL, G. 1926 The relation of the soil nitrogen to nodule development and fixation of nitrogen by certain legumes. *N. J. Agr. Exp. Sta. Bul.* 436: 3–125.

(5) HILTNER, L. 1900 Ueber die Ursachen, welche die Grösse, Zahl, Stellung und Wirkung der Wurzelknöllchen der Leguminosen bedingen. *Arb. K. Gsndhtsamt. Biol. Abt.* 1: 177–222.

(6) HOPKINS, E. W., AND FRED, E. B. 1933 Influence of various nitrogenous compounds and mannitol on nodule formation by clover. *Plant Physiol.* 8: 141–155.

(7) HOPKINS, E. W., WILSON, P. W., AND PETERSON, W. H. 1932 Influence of potassium nitrate on nodule formation and nitrogen fixation by clover. *Plant Physiol.* 7: 597–611.

(8) KRAUS, E. J., AND KRAYBILL, H. R. 1918 Vegetation and reproduction with special reference to the tomato. Oreg. Agr. Exp. Sta. Bul. 149.

(9) LAURENT, E. 1891 Recherches sur les nodosités radicales des Légumineuses. *Ann. Inst. Pasteur* 5: 105–139.

(10) LUDWIG, C. A. An apparatus for growing plants by artificial light. In manuscript.

(11) MARCHALL, E. 1901 Influence des sels minéraux nutritifs sur la production des nodosités chez le pois. *Compt. Rend. Acad. Sci.* [Paris] 133: 1032–1033.

(12) MASON, T. G., AND MASKELL, E. J. 1928 Studies on the transport of carbohydrates in the cotton plant. *Ann. Bot.* 42: 189–253, 571–636.

(13) MAZÉ. 1898 Les microbes des nodosités des Légumineuses. *Ann. Inst. Pasteur* 12: 1–25, 128–155.

(14) MILLER, E. C. 1931 Plant Physiology. McGraw-Hill Book Co., New York.

(15) MÜLLER, D. 1932 Analyse der verminderten Stoffproduktion bei Stickstoffmangel. *Planta, Ztschr. Wiss. Biol., Abt. E,* 16: 1–9.

(16) PRUCHA, M. J. 1915 Physiological studies of Bacillus radicicola of Canada field pea. *N. Y. (Cornell) Agr. Exp. Sta. Mem.* 5: 1–83.

(17) REID, MARY E. 1924 Relation of kind of food reserves to regeneration in tomato plants. *Bot. Gaz.* 77: 103–110.

(18) REID, MARY E. 1924 Quantitative relations of carbohydrates to nitrogen in determining growth responses in tomato cuttings. *Bot. Gaz.* 77: 404–418.

(19) REID, MARY E. 1926 Growth of seedling in relation to composition of seed. *Bot. Gaz.* 81: 196–203.

(20) REID, MARY E. 1926 Growth of tomato cuttings in relation to stored carbohydrates and nitrogenous compounds. *Amer. Jour. Bot.* 13: 548–574.

(21) REID, MARY E. 1929 Growth of seedlings in light and in darkness in relation to available nitrogen and carbon. *Bot. Gaz.* 87: 81–118.

(22) STARRING, C. C. 1923 Influence of the carbohydrate-nitrate content of cuttings upon the production of roots. *Proc. Amer. Soc. Hort. Sci.* 20: 288–292.

(23) STROWD, W. H. 1920 The relation of nitrates to nodule production. *Soil Sci.* 10: 343–356.

(24) THORNTON, H. G. 1929 The rôle of the young lucerne plant in determining the infection of the root by the nodule-forming bacteria. *Proc. Roy. Soc., Ser. B.* 104: 481–492.

(25) TURNER, T. W. 1922 Studies of the mechanism of the physiological effects of certain mineral salts in altering the ratio of top growth to root growth in seed plants. *Amer. Jour. Bot.* 9: 415–445.

(26) WEBER, E. 1930 Salpeterdüngung als Beeinträchtigung der Stickstoffsammlung durch Leguminosen. *Centbl. Bakt.* (II) 82: 353–379.

(27) WELTON, F. A., AND MORRIS, V. H. 1930 Effect of fertility on the carbohydrate-nitrogen relation in the soybean. *Plant Physiol.* 5: 607–612.

(28) WILSON, J. K. 1917 Physiological studies of Bacillus radicicola of soybean (Soja Max Piper) and of factors influencing nodule production. *N. Y. (Cornell) Agr. Exp. Sta. Bul.* 386: 369–413.

PLANT FEEDING BY BRIQUETTE FERTILIZATION

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Two major problems in economic and efficient fertilization of sugar cane have been under study for several years at this experiment station. One problem relates to the matter of excessive leaching of applied potash to the soil, whereas the other embraces the intricate subject of soil phosphate fixation. In this contribution a discussion is offered upon a type of fertilization which appears to offer, among other advantages, a means of minimizing excessive leaching of potash and of materially reducing fixation in the soil of applied phosphates.

Statements appear in the literature supporting claims by investigators purporting to show that some plant roots have the ability to feed upon nutrients in the solid phase. Carefully planned experiments are in progress at this time in which the habits of the cane plant, in this respect, are under observation.

The author has examined submerged wooden water pipes in which the flow of water was hindered by a penetration of plant roots. The pipes later became entirely useless as a result of the complete choking of the bore. Abandoned macadam and concrete roadways will usually furnish a good illustration of the inherent forces present in germinating seeds whereby the solid paving material becomes parted or shattered in order that growing root systems may find a path to food and moisture. Cases of rock cleavage by the growing roots of various plants have also been observed. Since plant roots thus strike through rigid material which is met in natural environment, they should penetrate equally well into artificially placed solid material containing food substances which may be acceptable or required. It became apparent, then, that were a source of plant food to be intimately incorporated with a cementing medium, properly diluted, and, were such a mixture hardened by mechanical compression or natural cementation, it should furnish a means of fertilization in which loss of soluble nutrients would be greatly reduced and phosphate fixation perhaps entirely overcome as set forth.

Laboratory experiments were conducted in the preparation of firmly setting cement and fertilizer briquettes. In order to reduce chemical interaction of cement and fertilizer salts and later to minimize leaching of soluble constituents, a briquette was finally produced containing only, one soluble ingredient (potassium chloride). A formula found satisfactory at that time consisted of the following mixture:

Dried blood	50 parts by weight
Bone meal	50 parts by weight
Raw rock phosphate	50 parts by weight
Potassium chloride	50 parts by weight
Portland cement	125 parts by weight
Sand	50 parts by weight
Water	Sufficient

It was found that in the course of a few hours the briquette made by this formula would readily solidify in initial set and that in a day or two following it would have become sufficiently firm and dry for experimental use. When immersed in water the briquette retained its solid form without disintegration, but as was to be expected, there was a slow but constant loss of potash to the surrounding water. In other respects, however, the product appeared entirely satisfactory.

In order to ascertain the value in service of such a cemented mixture it was decided to make a "field" test of the briquettes in an attempted fertilization of water lilies under the bed of a flowing stream. The conditions of this test, we believed, were sufficiently severe to furnish direct evidence as to the value of the scheme, particularly regarding the ability of a plant to utilize fertilizer in such a form, even when submerged adjacent to running water. A section of the stream was found (about 30 feet in width) where pond lilies were already growing on either side. The condition and s ze of the plants at either bank were very nearly alike. All of the plants on one side were treated as follows: In an arc of about a 1-foot radius, up stream from the main plant stem, three depressions were made, small stones, soil, and sand being removed for a depth of about 10 to 12 inches. This treatment was given when the water was very low and stream flow practically negligible. A single briquette, weighing about 1 pound, was placed in the bottom of each depression, and the stones and soil were returned until all the excavations had been filled and smoothed off level with the bed. The plants on the other side of the stream were not treated in any manner. In the course of about 5 to 6 weeks the leaves of the plants in the treated area had grown larger than those having received no treatment. In the course of about 3 months the contrast in leaf size and number of leaves, as well as color, marked between the treated and untreated lilies. The treated plants produced many more flowers of a considerably larger size individually than those growing in the other area. After about a year had elapsed, at a period of very low water, an attempt was made to remove an entire root system of one of the treated plants. The attempt was not entirely successful, but we did find that the roots of the plant had grown to, and surrounded, the briquettes with a basket-like weave of comparatively large roots, and in the place formerly occupied by the briquette a mass of very find roots had grown. Nothing remained of the original briquette except a sandy residue. Upon pulling up other root clusters in the treated area we were enabled to shake all of the disintegrated residue of the briquette out of its basket-like enclosure by striking the whole assembly against the side of a rock.

The experiences gained from this experiment led to further trials of the briquette fertilization scheme in pot cultures with soil, eucalyptus and papaya trees being used this time as indicator plants.[1] Briquettes were prepared according to a formula similar to the one described, with the exception that no bone meal was used. The average dry weight of the briquettes was 414 gm. each, the plant food content being calculated as 1.4 per cent nitrogen, 4.25 per cent phosphoric acid, and 7.0 per cent potash.

Eight concrete tubs were selected having a capacity each of about 50 pounds of soil. Preparatory to filling the tubs, the soil was thoroughly mixed, screened, and then quartered. The experiment was laid out into four sets, in duplicate, on October 27, 1931, as follows:

Set 1: Control, no treatment; each pot planted to one papaya seedling.
Set 2: Six briquettes placed at the bottom of each pot and planted to one individual papaya seedling.
Set 3: Control, no treatment; identical to set 1, except planted to one young eucalyptus tree.
Set 4: Six briquettes placed in the bottom of the pot and then planted to one eucalyptus seedling.

In all cases, plants were selected of the same age and as nearly as possible of the same size and development.

The soil selected for this experiment was particularly weak in potash. About 2 months after being planted, the untreated eucalyptus developed a dark reddish coloration of all leaves and stems. Eucalyptus growing in pots containing briquettes were free from this symptom of disorder. Six months later a decided response to the briquette treatment had become evident in every case. The treated plants exhibited a more abundant growth and a better color and were taller and more bushy than the controls (pl. 1).

After the root systems of both eucalyptus and papaya had been given opportunity to develop in the presence of the briquettes for a period of about 1 year, a root assembly of each variety of tree was carefully removed from the pots and washed free of soil. The roots of the papaya had not grown to or around any of the briquettes, but in the case of the eucalyptus tree, fine roots had surrounded the briquettes and at various points along their outer surfaces root terminals had drilled into the firm mass for some distance. Figure 1 of plate 2 shows two such briquettes which were cut free from the main root system so that root attachment might be shown.

The development and growth of the trees were allowed to continue until the roots of the treated eucalyptus were severely pot bound. Figure 2 of plate 2 illustrates the relative growth of treated and untreated plants at the close of the experiment (18 months).

In the early stages of growth the response of the papaya to briquette fertilization was not pronounced. Later, however, the treated trees showed marked gains over the untreated. In the case of eucalyptus, response was immediate,

[1] This work was assigned to Mr. Carl W. Nesbitt, Staff Chemist, and was thereafter conducted by him.

and as the trees developed the comparison between treated and untreated plants became more manifest and striking.

Although it is true that this experiment gave indications that certain plants may feed upon briquettes in dry land practice, still there are certain marked disadvantages in using Portland cement in the preparation of fertilizer briquettes. The first objection is a chemical one. The highly alkaline cement reacts with many of the more common soluble and partially soluble fertilizer materials and so limits the range of fertilizers which may be employed. This fact renders it practically impossible to use soluble fertilizers in the fabrication of a Portland cement type of briquette. The second objection is found in the high calcium content of the cement, a factor which is not always desirable for certain plants or for field use in some localities.

The study, was continued,[2] following the completion of the experiment described in the foregoing. The first objective was to develop a means of substituting in the briquette mixture satisfactory cementing materials other than Portland cement.

A number of briquettes were prepared in which plaster of Paris was used as the binding and hardening medium. In order to arrest loss of nutrients by solution from this porous type of briquette they were coated (after setting and drying) with a heavy application of paraffin wax. This latter treatment, of course, would add to the handicap imposed upon any root system in extracting nutrient substances from the concentrated source of supply.

With sugar cane as an indicator in a series of 50-pound pots, the plaster of Paris briquettes were employed as an only source of applied fertilizer[3] in a low grade, unproductive soil.

The experiment consisted of:

(*a*) No treatment; duplicate pots.
(*b*) One briquette per pot weighing about 1 pound, but the entire briquette reduced to powder and applied to the soil.
(*c*) One briquette in each pot, placed near the bottom of the soil container.

In this experiment it was planned to take note of any differences which might develop as a result of introducing the fertilizer in one large unit, protected against excessive loss by seepage, as opposed to the same materials applied to the soil following as nearly as possible the practice used on a field scale. At 3 months of age the cane growing in the pots containing the solid briquettes showed a noticeable improvement over those growing in the pulverized briquette treatment. A greater number of suckers had grown from the stools, the leaves of the plants were greener, wider, and longer, and in all respects these plants, nourished by solid briquettes, showed a marked growth and vigor over the other two sets (pl. 3, fig. 1).

[2] Mr. Paul L. Gow, staff chemist, conducted this experiment.

[3] Briquettes were so fabricated that one would contain an equivalent amount of fertilizer per unit quantity of soil as would be applied in the general practice current throughout the Islands in fertilizing this crop.

Following these observations, laboratory studies on the preparation of new types and kinds of briquettes for experiment in the field were made. The encouraging progress in the study rendered it advisable at this point, we thought, to summarize results and to outline the project on a more comprehensive basis. The following points were noted:

1. To be produced in large quantities, a cheap method of manufacture must be found. Having in view a system similar to that used on the mainland in briquetting coal dust, we looked into that process with the view of employing it with our materials if it were found feasible.

2. It appeared of advantage to confine fillers and binders to a class of compounds which would:

Be inexpensive and readily obtainable locally.

Not react chemically with the fertilizer constituents in a manner resulting in a weakening of cementation, nor should these materials impair the fertilizers from functioning to their full capacity. However, we *were* seeking a chemical combination of fertilizer constituents and conditioning substances which would enhance cementation without detriment to the product. (It will be shown later how this objective was realized.)

3. The field of briquette usefulness appeared to include all fertilization in general, but it was particularly adapted to areas of boggy land, marshes, and infertile districts subject to excessive rainfall. Briquettes appeared also to offer advantages in fertilization of soils where fixation of applied phosphates may be pronounced.

4. The increase in cost by briquetting operations must be offset by distinct advantages accruing from the use of this method of plant nutrition.

It was planned to take up, first, the search for a satisfactory binder and filler, and thereafter, with the aid of a hydraulic apparatus for compressing briquettes, to carry on experimental studies in the fabrication of a more generally useful and practical product.

In a search for a binder to supplant Portland cement and other bulky compounds it was found that a granular, dry sodium silicate (of special formula) could be utilized in the preparation of an excellent briquette. It was found, too, that a native black basaltic rock, when combined with the silica binder, produced a briquette which would accomodate almost any type of soluble or insoluble fertilizer, either singly or in combination. (As a matter of fact the more popular or common soluble fertilizers will usually produce a more satisfactory briquette of the silica binder type than will a mixture consisting mainly of insoluble materials.) By compressing such mixtures under hydraulic pressure a very firm and stable briquette could be prepared. Such briquettes were found to resist disintegration in water over a long period of time and to give up their soluble fertilizer salts at a low rate. A typical mixture consists of the following materials:[4]

Ammophos 13/48	24.3 gm.
Nitrate of potash	21.2 gm.
Powdered sodium silicate (spec. formula)	11.2 gm.
Ground basalt	56.7 gm.

[4] Using this briquette, one per foot of line, lines 5 feet apart, is equivalent to an application of 100 pounds N, 225 pounds P_2O_5, and 175 pounds K_2O per acre.

Ratio:

Filler to fertilizer—1 to 1

- Hydraulic pressure ..... 4,000 pounds
- Weight of briquette ..... About 115 gm.
- Size of briquette ..... Cylinder; Diameter 2 inches; Height 1⅛ inches

About 300 of these briquettes were prepared and have been placed in a field experiment with sugar cane on the Island of Kauai.[5]

In calculating costs of this new type of briquette we found that the use of the granular silicate increased the outlay above fertilizer per acre by about $17. The cost of the filler (basaltic rock) was practically nil. We felt it necessary, therefore, to devise another type of briquette in which the expensive silicate could be eliminated.

It was found that the acid constituents in the fertilizer salts, when brought in contact, under hydraulic pressure, with moisture and powdered basaltic rock of one type very common in the Islands, liberated, upon dehydration, sufficient silicic acid from the basalt to bind the mass thoroughly. A typical formula of this newest type of briquette[6] follows:

Ammophos 13/48 ..... 24.3 gm.
Nitrate of potash ..... 21.2 gm.
Ground Moililii basalt ..... 91.0 gm.

Ratio:

Filler to fertilizer—2 to 1.

- Hydraulic pressure ..... 4,000 pounds
- Weight of briquette ..... About 140 grams
- Size of briquette ..... Cylinder; Diameter 2 inches; Height 1$\frac{7}{16}$ inches

A large replicated pot experiment is now being prepared with sugar cane as the crop and in which the latest briquettes are to be employed for comparison with equal quantities of granulated briquette materials, with regular fertilizer mixtures of equivalent plant food content, and with no treatment whatever.

In other field, forest and pot experiments now under way it is our purpose to gather information which may throw light on the type of briquettes which should be employed to lend themselves readily and efficiently to the feeding habits of the crop for which they may be used. The root habits of various crops must also be studied in relation to their ability to surround and penetrate the briquettes. The size of the briquette is also an important factor, as well as its rate of disintegration. For perennial plants such as shrubs, bushes, and

[5] At the request of, and under the direction of Mr. W. W. G. Moir, agricultural technologist, American Factors, Ltd.

[6] Briquettes made from this formula and used 1 foot apart in 5-foot lines would fertilize 1 acre at the same rate of applied N, P_2O_5, and K_2O as that resulting from the use of the silicate mixture previously described.

trees, a briquette should be employed which will slowly and continuously give up small amounts of nutrients over a period perhaps of several years, whereas with sugar cane a briquette must be employed which will be completely disintegrated and will have discharged its nutrients prior to the time that the crop is to be ripened and harvested. The matter of soil type must also be taken into consideration in this study.

Further study indicated that the size, shape, and consistency of briquettes may be varied to suit any particular need. Thus, to produce a rapidly disintegrating product, the amount of filler may be reduced to very small proportions or it may be eliminated entirely.

Should the requirements call for a very hard briquette, as may be needed for plants, shrubs, and, particularly, trees, the amount of basaltic silicous filler (and binder) may be increased several times over the ratio appearing in the formulas given. Such a practice automatically dilutes the active fertilizer constituents, produces a larger and harder briquette, and also slows down the rate at which the fertilizer may diffuse, be dissolved, or be extracted by penetrating roots from the cemented mass.

For needs lying within these two extremes the amount of binder and size of briquette may be adjusted similarly.

Figure 2 of plate 3 shows three briquettes, each carrying the same amount and weight of fertilizer, but combined with variable amounts of basaltic filler.

CONCLUSION

The briquetting of fertilizers appears to offer a means of supplying a plant with insoluble or soluble nutrients under conditions where ordinary fertilizer mixtures would prove prohibitive or impractical.

The scheme is suggested as an expedient in overcoming heavy potash leaching or excessive soil phosphate fixation.

Briquette fertilization is under trial in Hawaii for starting young trees on barren slopes. At the time of planting, a few briquettes of slowly disintegrating character are introduced in the post hole near the roots of the sapling. The objective is to sustain and boost the growth of the young tree until its root systems are capable of carrying on and have reached lower zones of more abundant moisture. It has been found practicable adequately to fertilize aquatic plants by introducing fertilizer briquettes under the bed of a flowing stream. Briquette fertilization compares favorably with normal practice in the few experiments so far conducted. In one case (described in this paper) the centralization of nutrient supply in briquettes resulted in a more favorable response by the plant than was realized from the same materials rendered granular and then applied in the usual manner.

SUMMARY

Mechanical and chemical means of briquetting fertilizers are described. The development may be adjusted to meet the requirements of almost any type

of soil, crop, or plant. The advantages of employing briquetted fertilizer over regular practice in special cases are discussed. Basic formulas are given which may be varied to suit the needs of the experimenter. Responses are described in plant growth by the briquette fertilization in a stream bed of running water. Photographs are offered, together with discussion, bearing upon results obtained by briquette fertilization of trees in dry land practice and with sugar cane in concrete tubs.

PLATE 1

EFFECT OF BRIQUETTE FERTILIZATION ON PAPAYA AND EUCALYPTUS SEEDLINGS

Photographed June 30, 1932, 8 months after planting. A very poor soil from Manoa Substation, Field 9G was employed. The soil is extremely low in P_2O_5 and K_2O and has never been fertilized. Reaction = 5.4 pH.

FIG. 1. Indicator plant: Papaya seedlings.

FIG. 2. Indicator plant: *Eucalyptus ovata*.

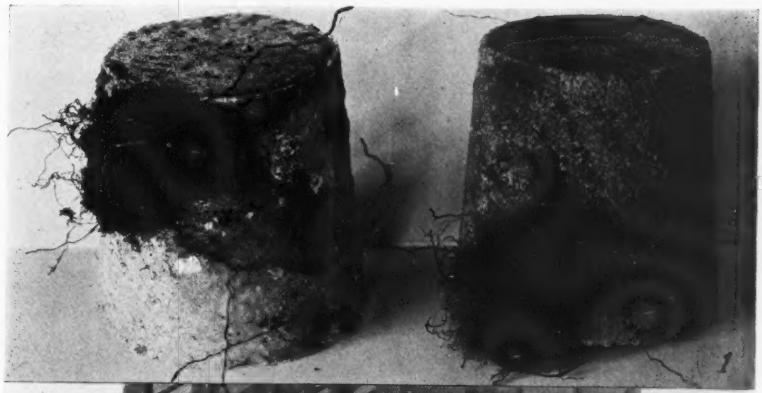
Control Treatment Control Treatment

Control Treatment Control Treatment

PLATE 2

FIG. 1. Cement type of slowly disintegrating fertilizer briquette, showing root attachment and incipient formation of surrounding basket-like "root weaving" 1 year after eucalyptus had been planted. Most of the root systems were removed from the attached portions before photographing.

FIG. 2. Indicator plants: Papaya seedlings and *Eucalyptus ovata*. The last set of plants used in the initial experiment, photographed March 28, 1933, 18 months after planting. The first set was harvested when 12 months old, October 24, 1932.



Treatment Control
Papaya

Treatment Control
Eucalyptus

PLATE 3

FIG. 1. Briquette fertilization of sugar cane; 3 months after planting.

X = no treatment.

F = Granulated briquettes incorporated with soil.

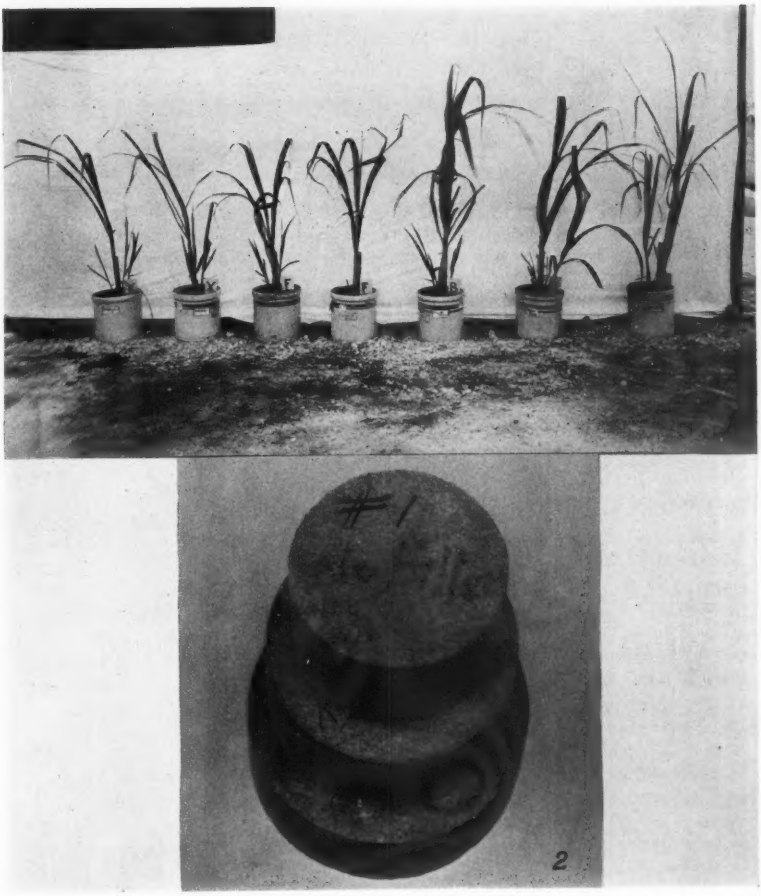
B = Solid briquettes (not granulated) prepared with plaster of Paris and coated with a heavy layer of paraffin. Comparable and identical in nutrient supply to the "F" treatment.

FIG. 2. Types of briquettes.

The small briquette (top) consists of fertilizer only (no filler). Weight = 63.75 gm. Size = diameter, 4.2 cm.; height, 2.66 cm.

The next larger and lower briquette carries equal quantities of filler and fertilizer. Weight = 116.8 gm. Size = diameter, 5.16 cm.; height, 2.92 cm.

The bottom (largest briquette) is a mixture of 2 parts filler to 1 of fertilizer. Weight = 176.4 gm. Size = diameter, 6.04 cm.; height, 2.86 cm.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THE INFLUENCE OF THE pH OF A CULTURE SOLUTION ON THE ASSIMILATION OF AMMONIUM AND NITRATE NITROGEN BY THE TOMATO PLANT[1]

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In an earlier publication (3) the influence of the pH of a culture solution on the rates of absorption of ammonium nitrogen (NH_4-N) and of nitrate nitrogen (NO_3-N) by the tomato plant (*Lycopersicum esculentum*, Mill.) was reported. As it is quite conceivable that not only the pH of the culture medium, but also the concentrations of NH_4-N, of NO_3-N, or of other nitrogenous constituents of the tissues of the plants used for the absorption tests might have influenced the rates of absorption of either or both forms of nitrogen, data will now be presented giving the proportions of certain nitrogenous fractions in the plants used for these absorption tests. The relationships between the rates of absorption of NH_4-N and of NO_3-N and the concentrations of these forms of nitrogen in the plants will be pointed out, and an attempt will be made to correlate the observed relationships with the assimilation of nitrogen by the plants, as indicated by certain nitrogenous fractions in aqueous extracts of the plant tissues, by the amounts of protein nitrogen in the tissues, and by the green weights of the plants.

Many experiments have been reported on the effect of the pH of soils or of culture solutions on plant growth, but only a few typical ones with higher plants grown in solution or sand cultures which have a direct relation to this study with tomatoes will be mentioned. Mazé (9), Hutchinson and Miller (7), and others have reported greater yields of plants grown in culture solutions including NH_4-N when $CaCO_3$ has been added to the solutions than when it has been withheld.

Prianischnikow (17) obtained greater yields of sugar beets when they were supplied with a pH 7.0 culture solution including only NH_4-N than when they were supplied with the same solution including only NO_3-N. In contrast, when the pH of the solution was lowered to 5.0 or 5.5, greater yields were obtained when the plants were given NO_3-N than when they were given NH_4-N. Furthermore, the yields from the solutions including NH_4-N were greater at pH 7 than at pH 5, and the yields from the solutions including NO_3-N were greater at pH 5 than at pH 7. Dikussar (5) using continuously renewed solutions confirmed these results.

Mevius and Engel (10), from experiments with maize plants, concluded that the rate of penetration of ammonia into the root cells was increased as the pH of the solution was increased, but they stated that protein was not necessarily formed if abundant carbohydrates were not available. Their work included analyses of the plants for several nitrogenous fractions.

Tiedjens and Robbins (21) grew several different crop plants in solutions of different pH and used either NH_4-N, NO_3-N, or both in the complete culture solutions, which were applied by the sand culture method. From the growth of the plants and from analytical data they concluded that ammonia was most efficiently assimilated at pH 7 or above, and that

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[1] Journal Series paper of the New Jersey Agricultural Experiment Station department of plant physiology.

[2] It is a pleasure here to acknowledge the valuable suggestions received from Dr. G. T. Nightingale concerning analytical procedures employed.

ammonia, although absorbed, was not assimilated at pH 4. They also found that nitrates were most efficiently assimilated at pH 5, but that ammonia at pH 8 was assimilated more rapidly in the tomato plant than were nitrates at pH 4 to pH 5.

Pirschle (14), in confirmation of earlier results, found that at strongly acid and at alkaline reactions, the growth of plants supplied with NH_4-N was less than that of plants supplied with NO_3-N. He noted that the pH optimum was about 5.5 to 6.5, within which range the differences between plants grown with NH_4-N and plants grown with NO_3-N were least.

Beaumont (1) found that $(NH_4)_2SO_4$, NH_4Cl, and $(NH_4)H_2PO_4$ were toxic to tobacco grown in culture solutions, although the young plants grew well for a while if $CaCO_3$ was added to the solutions. From analyses of the plants it was suggested that the toxicity of the ammonium salts was due to poor assimilation of the ammonium ion and consequent improper metabolism.

From the aforementioned experiments it can be concluded that the pH of the culture medium has a pronounced influence upon the assimilation of both NH_4-N and NO_3-N by higher plants, although not all of the investigators mentioned have agreed on the pH range at which the assimilation of NH_4-N, especially, has been most efficient. This is not surprising, considering the relationship which the type of plant and its supply of carbohydrates (8, 10, 12, 14, 16, 21) may have to the assimilation of nitrogen.

METHODS OF EXPERIMENTATION

Method of Growing Plants and Testing Absorption

The technique employed in growing the plants and in testing their rates of absorption of NH_4-N and of NO_3-N was described in the preceding paper (3). As was mentioned there, the plants used for these absorption tests, as well as others grown in corresponding solutions, were harvested within a few hours after each absorption test was completed and were immediately prepared for analysis. From the end of the absorption interval until the time of harvesting, the plants were grown in the same solutions as those used preceding and during the absorption tests.

Preparation of Tissue for Analysis

The plants to be analyzed were first separated into roots and tops. The latter were further separated into two fractions, (*a*) stems and petioles and (*b*) leaf blades. The stem and petiole fractions included all tissue to which the blades were not directly attached, whereas the leaf blade fractions included only the blades. The roots were well rinsed with a stream of tap water and then with distilled water and were dried between paper towels until adhering water had been removed.

The green weights of the separated fractions were all recorded and the tissues were then very finely minced. Duplicate 100-gm. aliquots of the stem and petiole fractions and duplicate 60-gm. aliquots of the blade fractions were immediately placed in an oven at 100°C. This temperature was decreased to 80–85°C. in about an hour, before the tissue had dried thoroughly. After being dried for 3 days at the lower temperature, the tissue was weighed, ground in a

drug mill, and used for total nitrogen analyses. The percentage dry matter data, as well as total nitrogen analyses of duplicate aliquots, showed that the aliquoting was very uniform.

One 100-gm. aliquot of each portion of minced tissue was immediately placed in boiling water and was subsequently extracted by wringing and washing. A comparison of this method of extraction with that in which sand is first used to grind the tissue is to be published (4). Extraction of all the samples was usually completed within 12 hours after the tissue had been boiled. Tests with replicate aliquots of minced corn tissue showed that once the fresh tissue had been boiled, extraction even after 48 hours gave the same results for the various fractions as extraction immediately after boiling.

Chemical Methods

Ammonia nitrogen. The liter extract obtained from each 100-gm. portion of tissue was boiled and the coagulable nitrogen removed as previously described (4). Duplicate 100-cc. aliquots were then taken, and ammonia nitrogen was removed by a modification of the method of Sessions and Shive (19). Eighth-normal NaOH was substituted for the Na_2CO_3 and NaCl originally suggested, with aspiration at room temperature for a period of at least 16 hours. This modification was adopted as a result of the work of Tiedjens and Robbins (21), who found that a fraction which they called "combined ammonia" could be removed by aspiration with NaOH after the unmodified (19) aspiration with Na_2CO_3 and before the addition of Devarda's alloy for the reduction of nitrates. This fraction, which they sometimes found to be even greater than the ammonia removed by Na_2CO_3, obviously should not be included with the nitrate nitrogen, as would occur if the unmodified (19) procedure were used. By the use of NaOH in the aspiration for ammonia, this "combined ammonia," if present, was included in the ammonia fraction in the data reported here. Sessions and Shive (19) have shown that little breakdown of certain amino acids occurred when these were aspirated with 0.125*N* NaOH and Devarda's alloy. Furthermore, the comparatively small amounts of ammonia nitrogen reported in the following tables do not indicate the inclusion of any considerable amount of nitrogen which should have been reported in some other fraction. The terms, "ammonia nitrogen," and "NH_4-N," are used interchangeably.

Nitrate nitrogen. After removal of the ammonia nitrogen from the aforementioned aliquots, 2.5 gm. of Devarda's alloy was added and aspiration continued for another period of 16 hours according to the method outlined by Sessions and Shive (19). However, the results obtained from the extracts of the stems, which contained an exceedingly large amount of nitrate nitrogen, were not compatible with the results from the other fractions in that the total inorganic nitrogen from the aqueous extract was too high. Therefore, analyses for nitrate nitrogen in all of the stems were repeated on the dried tissue. Because of the buffering action of the plant material, nearly twice as much NaOH was used as in the original determinations. The results for nitrate nitrogen which appear in table 4 are those obtained from the dried tissue.

Amide nitrogen. Immediately after the removal of the aforementioned aliquots, the remaining volume of each extract (800 cc.) was evaporated to 200 cc. and divided into duplicate 100-cc. aliquots, to each of which was added enough conc. H_2SO_4 to give a 5 per cent solution. Suitable tests showed that this concentration prevented any significant changes in the distribution of nitrogen in the concentrated extracts, some of which were necessarily left in this stage while others were being subjected to the treatments which followed.

These concentrated aliquots were hydrolyzed for 2½ hours, cooled, and neutralized with 30 per cent NaOH. The ammonia then present, including both ammonia nitrogen and amide nitrogen, was removed by aspiration as described in the foregoing, and the previously determined ammonia was deducted. Since these tissues contained abundant nitrates, the use of H_2SO_4 in the hydrolysis was essential, as has been shown by Vickery and Pucher (24) and Chibnall and Miller (2).

Humin nitrogen. After the solutions had been aspirated for the removal of amide nitrogen, they were neutralized with conc. H_2SO_4, made slightly acid with one drop in excess, and evaporated to 100 cc. The slight precipitate formed was filtered off and washed on No. 1 Whatman filter paper. Total nitrogen determinations on this precipitate by the method next described showed the presence of a negligible quantity of nitrogen (about 0.001 per cent in the roots and stems and 0.005 per cent in the leaves). Therefore, no values are reported for humin nitrogen. According to the procedure of fractionation employed, the result of this omission of the humin fraction was to add the humin nitrogen of the aqueous extract to the protein nitrogen. The latter fraction being many times as great, no appreciable error was introduced.

Total soluble nitrogen. The humin-free filtrate was made up to a volume of 100 cc., and an aliquot of 25 cc. was taken from each duplicate for a total nitrogen determination. To the result was added the nitrogen previously removed in the amide determination. In as much as the extracts included nitrates, the modified Kjeldahl-Gunning method for including nitrates, as outlined by Ranker (18), was used. The solution was kept slightly acid during evaporation, a precaution necessary to avoid the loss of nitrogen.

Total amino nitrogen. Aliquots of the humin-free filtrate were used for this determination. The method of Van Slyke (22) was employed, and it was found to be advantageous to substitute a burette taken from a micro-size apparatus for the large burette found on the macro-size apparatus employed. This permitted the use of large aliquots for analysis and an accurate estimation of small quantities of gas. In as much as this fraction included some nitrogen properly placed in the next fraction, the results of the total amino determinations do not appear in the tables.

Basic nitrogen. A 50-cc. aliquot from each of the duplicates of the humin-free filtrate was also removed and the basic nitrogen precipitated with phosphotungstic acid precipitating solution prepared according to the directions of Osborne and Harris (13). Fifteen cubic centimeters of the precipitating solu-

tion were sufficient for these aliquots. The solution including the precipitate was allowed to stand, with occasional stirring, for several days, and was then filtered off on No. 42 Whatman filter paper. All the precipitate was removed from the beaker with the aid of a moistened filter paper, but no washing was attempted, for this often disperses the precipitate into the filtrate. Analyses of the filtrate for nitrates showed that even when the precipitate was not washed a negligible adsorption of nitrates, at least, occurred.

Basic-free amino nitrogen. The filtrate from the basic precipitate was neutralized with 30 per cent NaOH, made slightly acid with a drop of conc. H_2SO_4, and evaporated to a volume of 50 cc. An aliquot of 25 cc. was sometimes used for another total nitrogen determination to check the amount of basic nitrogen obtained by analysis of the precipitate, but the remainder of the filtrate was available for a second amino determination carried out as described in the foregoing. Only the values for basic-free amino nitrogen appear in the tables.

Protein nitrogen. Total nitrogen was determined on aliquots of the dried tissue by the same method (18) as that employed for total soluble nitrogen. The difference between the total and total soluble (non-coagulable) nitrogen is regarded as protein nitrogen (11).

Soluble organic nitrogen. This fraction was calculated by subtracting the sum of the ammonia and nitrate determinations from the total soluble nitrogen.

Other nitrogen. This was calculated by subtracting the sum of the soluble nitrogen fractions reported from the total soluble nitrogen determined analytically. Consequently, it includes nitrogen not recoverable by the methods employed as well as the result of experimental error in the other determinations.

EXPERIMENTAL RESULTS

Absorption Data

Descriptions of the appearance of the plants at the time of harvesting have been given in the preceding paper (3). Some of the data, however, have been selected from the tables in that article and these are repeated in table 1, in the order which is adapted for comparison with the data presented in the following tables. In table 1 are listed only the data on absorption by those plants for which the analyses of plant tissue are reported. Absorption data in table 1 are the averages of triplicate cultures each including three plants, whereas the green weight figures are the averages of five cultures when the plants were 41 days old, and three cultures when the plants were 52 days old. The culture solution used included approximately 75 mgm. per liter of both NH_4-N and NO_3-N.

Composition of Roots in Relation to Absorption

The several nitrogenous fractions obtained from the aqueous extracts of the roots made at the time of each harvest are listed in table 2, together with the average green weight of the roots per plant. The nitrogen in each fraction is expressed as a percentage of the green weight of the tissue in every case. The

values given for plants in each of the treatments at the age of 41 days are based on an extract from a composite sample of tissue from five cultures, each including three plants. Three of these cultures had been used for the absorption test on the day of the harvest. The values for the plants at the age of 52 days are based on tissue from three cultures, each including three plants. All three cultures had been used for the second absorption test on the day of the harvest.

TABLE 1

Rates of absorption of nitrogen by plants used for absorption tests

Absorption expressed as mgm. N absorbed per 100 gm. green tissue in 6 hours from a solution including equal proportions of NH_4-N and NO_3-N.

	AGE OF PLANTS					
	41 days				52 days	
pH of solutions	4.0	5.0	6.0	7.0	4.0	7.0
Average green weight per plant in gm.	53.0	55.1	64.6	57.8	139.0	117.8
NH_4-N absorption	3.4	4.2	4.6	6.6	2.2	5.0
NO_3-N absorption	4.8	5.9	4.1	3.0	7.6	8.4
Total N absorption	8.2	10.1	8.7	9.6	9.8	13.4

TABLE 2

Nitrogenous fractions in roots of plants used for absorption tests

Nitrogen expressed as percentage of tissue on green weight basis

	AGE OF PLANTS					
	41 days				52 days	
pH of solutions	4.0	5.0	6.0	7.0	4.0	7.0
Average green weight of roots per plant in gm	7.4	7.9	11.5	11.0	17.2	17.5
Total soluble N	0.100	0.117	0.132	0.142	0.105	0.139
Soluble organic N	0.045	0.060	0.059	0.060	0.060	0.072
Basic-free amino N	0.020	0.027	0.034	0.038	0.023	0.040
Basic N	0.020	0.024	0.020	0.016	0.027	0.019
Amide N	0.005	0.007	0.006	0.006	0.006	0.011
Other N	0.001	0.002	−0.001	0.001	0.005	0.001
Ammonia N	0.013	0.018	0.031	0.042	0.014	0.039
Nitrate N	0.043	0.040	0.042	0.040	0.031	0.028

In as much as the data included in table 2 are too extensive and diversified to be considered as a unit, certain sections will be selected and treated separately.

Nitrate nitrogen. To correlate, if possible, the rates of absorption of NO_3-N with the concentrations of NO_3-N in the root tissue of the plants used for the absorption tests, figure 1 is presented. It is based on data taken from tables 1 and 2. It should be emphasized that the absorption rates were calculated on the basis of the green weight of the whole plants, not of the roots.

The diagram shows that there was no correlation between the rates of absorption of NO_3-N from the solutions and the concentrations of NO_3-N in the roots. It is evident that the variations in concentration of NO_3-N in the roots of the plants 41 days old with variations in pH of the culture medium were not significant, despite marked differences in the rates of absorption of NO_3-N from solutions of different pH.

Moreover, the difference between the concentration of NO_3-N in the roots of the plants 52 days old grown in the pH 7 solution and that of those grown in the pH 4 solution was not significant. However, the concentrations of NO_3-N in the roots of plants grown in solutions of corresponding pH decreased significantly as the plants grew older.

The fact that no more NO_3-N accumulated in the roots of plants which were absorbing NO_3-N at a high rate than in those which were absorbing it at a much

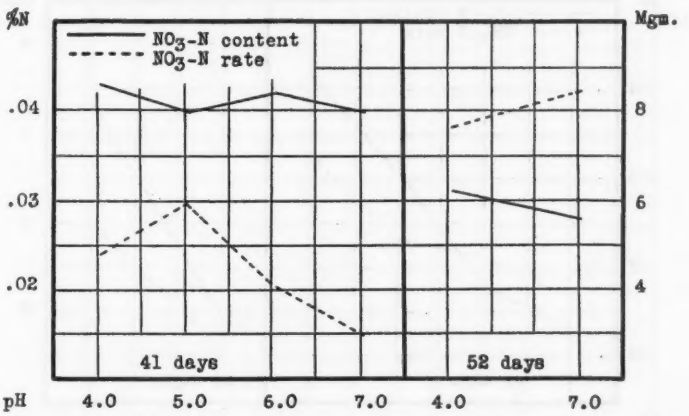

FIG. 1. NITRATE NITROGEN IN TOMATO ROOTS, EXPRESSED AS PERCENTAGE OF GREEN TISSUE, AND RATES OF ABSORPTION OF NO_3-N FROM CULTURE SOLUTIONS, EXPRESSED IN MILLIGRAMS OF NITROGEN ABSORBED PER 100 GM. OF GREEN TISSUE IN 6 HOURS

lower rate suggests that such an accumulation was prevented either by more rapid translocation or by more rapid reduction of the NO_3-N when the rate of absorption of NO_3-N was high than when it was low. From a consideration of the data on the composition of the tops as given in the following, the latter alternative appears to be the more probable one.

Mention should be made of the high concentration of NO_3-N in the roots of the plants as compared with that in the external solution, despite which high rates of absorption of NO_3-N occurred. A concentration of 0.040 per cent is equivalent to 400 mgm. of NO_3-N in 1,000 gm. of green tissue, of which only about 5 per cent is dry matter. Hence, the concentration of NO_3-N in the tissue was more than 400 mgm. per liter of water. In contrast, the concentration of NO_3-N in the external solution was approximately 75 mgm. per liter.

Ammonia nitrogen. Figure 2 presents the rates of absorption of NH_4-N in relation to the concentrations of NH_4-N in the roots of the plants, the method of plotting being the same as in figure 1. Figure 2 clearly shows that the pH of the culture medium had a pronounced influence upon the concentration of NH_4-N in the root tissue and that this influence was directly related to the rates of absorption of NH_4-N from the culture solutions. For example, the concentration of NH_4-N in the roots of the plants 41 days old grown in the pH 7 solution was three times that in the roots of plants of the same age grown in the pH 4 solution. At the same time, the rate of absorption of NH_4-N was about twice as high from the pH 7 solution as from the pH 4 solution.

In other words, the more rapidly NH_4-N was absorbed by the plants, the more was present in the roots per unit of plant tissue. The ratio of absorption

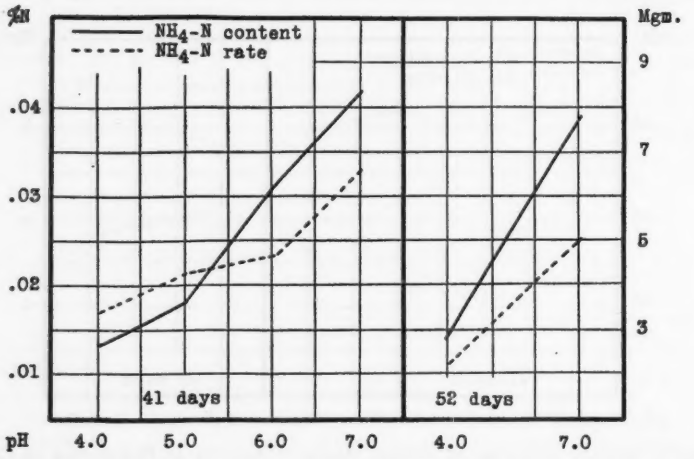

FIG. 2. AMMONIA NITROGEN IN TOMATO ROOTS, EXPRESSED AS PERCENTAGE OF GREEN TISSUE, AND RATES OF ABSORPTION OF NH_4-N FROM CULTURE SOLUTIONS, EXPRESSED IN MILLIGRAMS OF NITROGEN ABSORBED PER 100 GM. OF GREEN TISSUE IN 6 HOURS

to concentration in the roots was not a constant for plants grown in solutions of different pH. Indeed, that should not be expected, since it is quite probable that some of the NH_4-N in the roots arises from the reduction of nitrates absorbed. Eckerson (6) states that reducase is present in the tops and roots of the tomato in about equal proportions.

It is noteworthy that the high concentration of NH_4-N in the roots of the plants grown in the pH 7 solution did not prevent a very rapid rate of absorption of NH_4-N from the external solution. The ratio of the concentration of NH_4-N in the root tissue of these plants to that in the external medium, calculated in the same manner as given for NO_3-N, was of the same order as the NO_3-N ratio.

Figure 2 brings out one other point, that the concentration of NH_4-N in the roots did not increase as the plants grew older, within the limits of this experiment. Instead, the concentrations of NH_4-N in roots of plants grown in solutions of corresponding pH values were quite alike at 41 days and at 52 days.

Basic-free amino nitrogen. To show that the accumulation of NH_4-N in the roots of the plants grown in the high pH solutions did not result simply in a piling up of inorganic nitrogen within the roots, figure 3 is presented, the data for which were taken from table 2. Figure 3 shows the close connection between the concentration of NH_4-N in the tissue and the concentration of amino

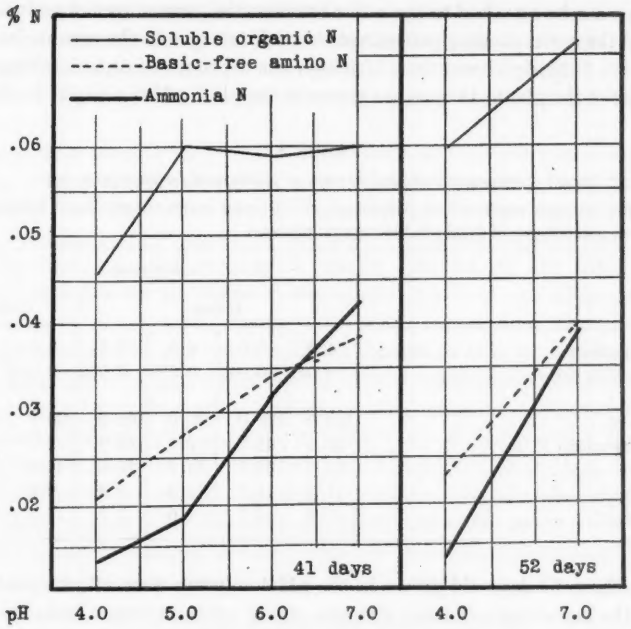

FIG. 3. AMMONIA NITROGEN, BASIC-FREE AMINO NITROGEN, AND SOLUBLE ORGANIC NITROGEN IN TOMATO ROOTS, EXPRESSED AS PERCENTAGE OF GREEN TISSUE

nitrogen in the tissue. In every case, a high concentration of NH_4-N was accompanied by a high concentration of amino nitrogen. This suggests a rapid formation of amino nitrogen in the roots from the NH_4-N present, the amount of amino nitrogen formed being greatly increased by the presence of increasing amounts of NH_4-N.

Soluble organic nitrogen. The graph of figure 3 which represents the percentages of total soluble organic nitrogen in the tissues of the roots shows, in comparison with the other fractions represented, that the amount of soluble organic nitrogen present was, in a measure, related to the concentration of

amino nitrogen present. However, as table 2 shows, other fractions than amino nitrogen comprise a considerable portion of the soluble organic nitrogen, consequently the total organic nitrogen present was not always proportional to the amount of amino nitrogen included in it.

In order to show the percentage of the total soluble organic nitrogen comprised in each fraction, the data of table 3 were calculated from those of table 2. Table 3 brings out more clearly than does table 2 the inverse relationship that existed between the percentages of amino nitrogen and basic nitrogen included in the soluble organic nitrogen fraction. In those cases in which the total organic nitrogen differed in plants grown in the different solutions, no significance can be attached to the ratios between the percentages of amino nitrogen and the corresponding percentages of basic nitrogen in the organic fraction. But table 3 clearly shows that, although the amounts of organic nitrogen in the roots of the plants 41 days old grown in the pH 5, pH 6, and pH 7 solutions

TABLE 3

Organic nitrogenous fractions in roots of plants used for absorption tests

Organic nitrogen expressed as percentage of tissue on green weight basis; fractions expressed as percentages of total soluble organic nitrogen.

	AGE OF PLANTS					
	41 days				52 days	
pH of solutions	4.0	5.0	6.0	7.0	4.0	7.0
Organic N in tissue	0.045	0.060	0.059	0.060	0.060	0.072
Organic N	100.0	100.0	100.0	100.0	100.0	100.0
Basic-free amino N	43.2	45.2	57.5	62.9	38.5	56.4
Basic N	43.9	39.5	34.2	26.0	44.2	26.6
Amide N	11.5	11.2	9.3	9.4	9.8	15.4
Other N	1.4	4.1	−1.0	1.7	7.5	1.6

and in those 52 days old grown in the pH 4 solution were all practically the same, the percentages of basic nitrogen and of amino nitrogen included in the total soluble organic nitrogen were quite different in plants grown in solutions of different pH. The data show that the percentage of basic nitrogen was relatively low when the percentage of amino nitrogen was high, and vice versa.

This reciprocal relationship was definitely and consistently correlated with the pH of the culture solutions, and, consequently, with the rates of absorption of NH_4-N and of NO_3-N. It is noteworthy that the percentages, as well as the absolute amounts, of basic nitrogen were lowest in the plants 41 days old grown in the pH 7 solution. In these same plants the concentrations of NH_4-N and of amino nitrogen were the highest, and the rate of absorption of NO_3-N was the lowest. This observation suggests that, although NH_4-N may readily pass over into the amino form in the roots of the tomato, it is not readily elaborated there into more complex forms.

Furthermore, the degree of elaboration of the basic nitrogen present in the roots of the plants 41 days old can be correlated with the aforementioned results. A consideration of the method of fractionating the extracts will show that the difference between the total amino nitrogen (not reported in the tables) and the basic-free amino nitrogen gives the alpha-amino nitrogen which was included in the basic precipitate. The results of such calculations showed that in the roots of the plants 41 days old the alpha-amino nitrogen included in the basic fraction comprised a much higher percentage of the basic nitrogen when the plants were grown in the pH 7 solution than when they were grown in the pH 4 solution, and that a gradient was evident in the intermediate solutions. The alpha-amino nitrogen included in the basic precipitates from the extracts of the roots ranged from 24.7 per cent of the basic nitrogen in the plants grown in the pH 4 solution to 65.8 per cent in the plants grown in the pH 7 solution. The same trend, although less pronounced, was evident in the plants 52 days old.

These data indicate that more diamino acids and less complex compounds, having several nitrogen atoms for each alpha-amino radical, must have been present in the basic fraction from the roots of the plants grown in the pH 7 solution than from those grown in the pH 4 solution. That is, not only did the basic nitrogen comprise a smaller fraction of the total soluble organic nitrogen in the roots of the plants grown in the high pH solution than in those grown in the low pH solution, but also the basic nitrogen precipitated was less complex in the former than in the latter. It is recognized, however, that the analytical methods on which these data are based have certain limitations when applied to plant extracts. Plimmer (15) has presented evidence of the inclusion of other forms of nitrogen than the alpha-amino form in the nitrogen obtained by the Van Slyke (22) method, and Vickery (23) has shown that the nitrogen precipitated by phosphotungstic acid from plant extracts is not composed simply of basic amino acids. The concentrations of amide nitrogen not only were low throughout the plants, but also were not influenced by the pH of the culture solution.

Composition of Stems and Leaves

Although it is possible to trace a relationship between the rates of absorption of NH_4-N, the concentrations of NH_4-N, and, to some degree, the concentrations of amino and basic introgen in the tissues of the roots of the plants, the course of assimilation of nitrogen in the tops is not evident. The amounts of nitrogen included in the various nitrogenous fractions, expressed as percentages of the green weight of the tissue, in the stems and petioles are presented in table 4. For brevity, these fractions are referred to as "stems." Similar data from the leaves are given in table 5. Values for protein nitrogen in the stems and leaves, a fraction which was not determined in the roots because of the lack of sufficient material, are included. The average values presented in these tables are based on the same number of plants as are those of table 2.

No graphs are presented to illustrate the relation between rates of absorption of nitrogen and the amounts of inorganic nitrogen in the tissues of the tops because the variation in inorganic nitrogen in the tops with variation in pH of the external medium cannot be closely correlated with absorption by the roots. Instead, the composition of the three different fractions of the plants—roots, stems, and leaves may be compared in an attempt to trace the assimilation of nitrogen throughout the plants.

The data for NO_3-N in tables 2, 4, and 5 reveal that there was not a decreasing concentration of NO_3-N in the plants from roots to leaves. Instead, NO_3-N accumulated in extremely high quantities in the stems as compared with the roots and leaves, a phenomenon probably related to the different amounts of

TABLE 4

Nitrogenous fractions in stems of plants used for absorption tests

Nitrogen expressed as percentage of tissue on green weight basis

	AGE OF PLANTS					
	41 days				52 days	
pH of solutions	4.0	5.0	6.0	7.0	4.0	7.0
Average green weight of stems per plant in gm	26.2	27.2	30.7	26.8	69.7	61.0
Per cent dry matter	5.55	5.23	5.00	4.87	7.17	6.92
Total N	0.248	0.244	0.236	0.221	0.310	0.275
Protein N	0.037	0.043	0.028	0.022	0.096	0.080
Total soluble N	0.211	0.201	0.209	0.199	0.215	0.195
Soluble organic N	0.068	0.064	0.068	0.068	0.068	0.080
Basic-free amino N	0.024	0.021	0.021	0.020	0.039	0.039
Basic N	0.015	0.010	0.012	0.012	0.016	0.016
Amide N	0.008	0.007	0.007	0.005	0.014	0.016
Other N	0.021	0.025	0.029	0.032	−0.001	0.009
Ammonia N	0.016	0.015	0.015	0.015	0.022	0.019
Nitrate N	0.128	0.123	0.126	0.115	0.124	0.096

reducase in the different parts of the plant (6). Furthermore, the rather small differences in concentration of NO_3-N in the roots between plants grown in solutions of different pH were paralleled by relatively small differences in the corresponding stems and leaves, with one apparent exception: the low concentration of NO_3-N in the stems of the plants 52 days old grown in the pH 7 solution, an interpretation of which is suggested in the discussion of figure 4.

Since tomato stems normally accumulate considerable quantities of NO_3-N (12, 21) when grown in a culture solution including nitrogen in this form, it is difficult to trace the course of assimilation of NO_3-N in these plants. However, the fact that no greater accumulations of NO_3-N occurred in plants absorbing NO_3-N more rapidly than occurred in others absorbing NO_3-N less rapidly

suggests that the pH range which favored the most rapid rate of absorption of NO_3-N also favored the most rapid assimilation of NO_3-N. The results obtained by Tiedjens and Robbins (21), using $Ca(NO_3)_2$ as a source of nitrogen, were quite similar. They found that tomato plants supplied with only NO_3-N were larger when grown in pH 4, pH 5, or pH 6 solutions than when grown in a pH 7 (or pH 3) solution. Less rapid absorption accompanied by less rapid and less complete assimilation of NO_3-N by plants grown in the pH 7 solution than by those grown in the pH 4, pH 5, and pH 6 solutions would produce the results they obtained. Their data show that stems which were lowest in green weight (those grown in the pH 7 solution) included the highest percentage of

TABLE 5

Nitrogenous fractions in leaves of plants used for absorption tests

Nitrogen expressed as percentage of tissue on green weight basis

	AGE OF PLANTS					
	41 days				52 days	
pH of solutions	4.0	5.0	6.0	7.0	4.0	7.0
Average green weight of leaves per plant in gm	19.4	19.8	22.4	20.0	52.0	39.2
Per cent dry matter	11.00	10.63	10.18	10.47	11.68	12.52
Total N	0.650	0.627	0.563	0.614	0.621	0.677
Protein N	0.533	0.515	0.425	0.495	0.479	0.554
Total soluble N	0.117	0.113	0.137	0.119	0.142	0.123
Soluble organic N	0.080	0.076	0.099	0.079	0.096	0.091
Basic-free amino N	0.027	0.025	0.028	0.028	0.033	0.038
Basic N	0.031	0.029	0.042	0.037	0.042	0.033
Amide N	0.007	0.007	0.007	0.006	0.011	0.012
Other N	0.016	0.015	0.023	0.007	0.010	0.008
Ammonia N	0.008	0.007	0.007	0.008	0.009	0.008
Nitrate N	0.029	0.029	0.031	0.032	0.037	0.024

NO_3-N. The foregoing data have shown that the rate of absorption of NO_3-N by younger plants, at least, decreased as the pH of the medium increased.

The data for NH_4-N in tables 2, 4, and 5 show that the concentration of NH_4-N in the tops was comparatively low and that for plants of a given age there was no significant difference in the content of this fraction between plants grown in solutions of different pH. A slightly greater concentration of NH_4-N was found in the stems of the plants 52 days old than in those 41 days old. It should be mentioned that a much greater accumulation of NH_4-N than was found in these particular plants sometimes occurs in the stems of tomato plants. Comparable plants grown in the pH 4 solution in sand culture until they were 70 days old included about three times as much NH_4-N in their stems as did those reported in table 4. This is another example of a phenomenon reported by Sessions and Shive (20).

In contrast to NO_3-N, NH_4-N did not accumulate in the stems or leaves of the plants in any appreciable excess of the concentration in the roots. It is significant that the large differences in concentration of NH_4-N in the roots between plants grown in solutions of different pH were not reflected in the tops. This indicates rapid assimilation of NH_4-N in the roots, further proof of which is found in the fact that high concentrations of amino nitrogen in the roots accompanied high concentrations of NH_4-N there. Although NH_4-N may also be present in cells as a catabolic product resulting from the breakdown of more complex nitrogenous constituents, NH_4-N from such sources could not have been abundant under the experimental conditions prevailing.

Although NH_4-N did accumulate somewhat in the roots of the plants which were absorbing it most rapidly, the accumulation was not excessive and did not result in any differences in concentration of NH_4-N in the tops of plants grown in solutions of different pH. Therefore, with respect to NH_4-N, also, it can be said that the pH range which favored the most rapid rate of absorption of NH_4-N also favored the most rapid assimilation of NH_4-N. This is in confirmation of the results obtained by Tiedjens and Robbins (21), using $(NH_4)_2SO_4$ as a source of nitrogen for tomato plants grown in solutions ranging from pH 4 to pH 8. They found that as the pH of the solution increased, the weight of the stems increased. More rapid absorption accompanied by more rapid and more complete assimilation of NH_4-N by plants grown in the solution of high pH than by those grown in solutions of low pH would produce greater growth of plants grown in solutions of high pH. Their data show that the largest plants, those from the solution of high pH, contained the least NH_4-N in the stems. The foregoing data have shown that the rate of absorption of NH_4-N greatly increased as the pH of the solution increased.

In general, the absence of many significant differences between nitrogenous fractions from the tops of plants grown in solutions of different pH is very evident. Such a condition was a natural result of the experimental conditions prevailing, namely: (*a*) the presence of equal concentrations of NH_4-N and of NO_3-N in the culture solutions in sufficient, but not excessive, quantities; (*b*) a pH range which was not great enough to produce toxicity or restricted growth in the plants; (*c*) the relatively long days prevailing during the spring; and (*d*) continuous aeration and continuous renewal of the solutions. Tiedjens and Robbins (21) also found comparatively small differences between the concentrations of corresponding nitrogenous fractions from the stems of tomato plants grown in different solutions of pH 4, pH 4.8, pH 6, and pH 7 when NH_4NO_3 was used as a source of nitrogen, in great contrast with the results obtained when either NO_3-N or NH_4-N was used alone.

As a result of the lack of significant differences in the tops, any discussion concerning the relation of the analytical results to the green weights of the plants would be largely speculation.

However, it might be of interest to trace the course of assimilation of NH_4-N and of NO_3-N further by studying the proportions of soluble organic nitrogen

in the tops as well as in the roots. Accordingly, the total soluble organic nitrogen values in the various organs of the plants grown in the several solutions have been plotted in figure 4. It is evident from this figure that there was a gradient in concentration of soluble organic nitrogen in the tissue from a low percentage in the roots to a high percentage in the leaves of plants in corresponding cultures. With one exception, the concentrations of soluble organic nitrogen in the stems were more nearly constantly proportional to those in the roots than to those in the leaves.

Although the soluble organic nitrogen has been treated in the foregoing discussion as a product resulting from the partial assimilation of inorganic nitrogen, it may also be considered as an intermediate product in the partial dissociation of the more complex proteinaceous nitrogen. The results obtained by

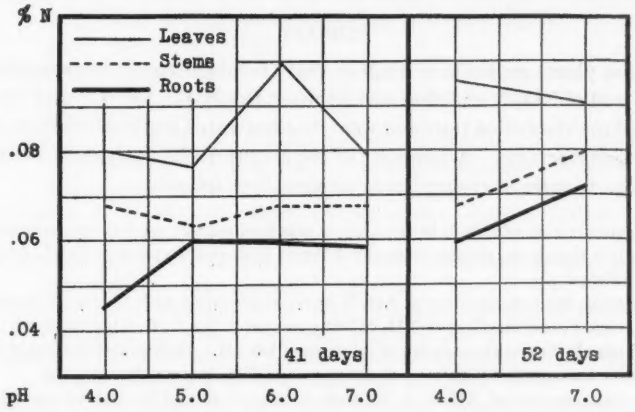

FIG. 4. TOTAL SOLUBLE ORGANIC NITROGEN, EXPRESSED AS PERCENTAGE OF GREEN TISSUE IN LEAVES, STEMS, AND ROOTS OF TOMATO PLANTS

Nightingale, Schermerhorn, and Robbins (12) with tomatoes, after the pioneer work of Kraus and Kraybill (8) have shown that an abundance of soluble organic nitrogen may be present either in weakly vegetative, non-fruitful plants kept in the dark, or in strongly vegetative, non-fruitful plants grown in the light. These workers have shown that the carbohydrate economy of the plants greatly affects the elaboration of protein, growth, and reproduction in plants.

No quantitative analyses for carbohydrates were made in these experiments, but microchemical tests made at the time of the first harvest showed very little starch present in the stems of the plants when 41 days old.

In vegetative plants growing in the light, as were these tomatoes, the end-products resulting from continued absorption and assimilation of nitrogen should be abundant protein nitrogen accompanying a fairly high concentration of soluble organic nitrogen. The data in tables 4 and 5 show the high proportions of protein nitrogen in the leaves as compared with that in the stems, as

well as the relatively large increase in protein nitrogen in the stems as the plants became older. It is evident that the soluble organic nitrogen in the stems of the plants 41 days old exceeded the protein nitrogen in the stems, but that the amount of soluble organic nitrogen in the leaves of the same plants was much less than that of protein nitrogen in the same tissue.

In conclusion, it appears from a consideration of the rates of absorption of NH_4-N and of NO_3-N in relation to the composition of the plants, particularly with respect to the concentrations of NH_4-N and of NO_3-N in the tissues, that each ion was most rapidly assimilated when most rapidly absorbed. This tendency emphasizes the fundamental importance of those properties of protoplasm which determine the rates of absorption of anions and cations from solutions of different hydrogen-ion concentration.

SUMMARY

Tomato plants grown in a solution that contained equal concentrations of NH_4-N and of NO_3-N and that was adjusted to pH 4.0, 5.0, 6.0, and 7.0 were first used for absorption tests and were then harvested and analyzed for certain nitrogenous fractions. A summary of the results of the analyses of the plants in relation to rates of absorption of nitrogen is as follows:

The concentration of NO_3-N in the roots of plants of a given age was approximately the same in all of the plants, despite markedly different rates of absorption of NO_3-N from solutions of different pH.

In contrast, the concentration of NH_4-N in the roots varied with the pH of the external medium, higher concentrations of NH_4-N being present in the roots of plants grown in solutions of high pH than in those grown in solutions of low pH. High concentrations of NH_4-N in the roots accompanied high rates of absorption of NH_4-N from the solutions.

High concentrations of NH_4-N in the roots were accompanied by high concentrations of basic-free amino nitrogen, an indication of a rapid formation of amino nitrogen in the roots from the NH_4-N present.

In the roots the percentage of total soluble organic nitrogen composed of basic nitrogen was relatively low whenever the percentage of amino nitrogen in the corresponding extract was high, and vice versa. This relationship was correlated with the pH of the culture solutions in that high concentrations of amino nitrogen were present in the roots of the plants grown in solutions of high pH, from which the rates of absorption of NH_4-N were high.

High proportions of amino nitrogen were included in the basic nitrogen in the roots of those plants which were grown in solutions of high pH and which contained high concentrations of NH_4-N and amino nitrogen.

NO_3-N accumulated in extremely high concentrations in the stems as compared with the roots and leaves, but the small variation in concentration of NO_3-N in the roots with variation in pH of the culture medium was paralleled by a relatively small variation in concentration in the stems and leaves.

Since no greater accumulation of NO_3-N in the plants resulted from high rates of absorption of NO_3-N than from low, it is evident that the pH range which favored the most rapid rate of absorption of NO_3-N also favored the most rapid assimilation of NO_3-N.

The concentration of NH_4-N in the tops was comparatively low, and for plants of a given age, there was no significant difference in this respect between plants grown in solutions of different pH, despite the differences found in the roots.

Since no greater accumulation of NH_4-N in the tops of the plants resulted from high rates

of absorption of NH_4-N than from low, and since high concentrations of amino nitrogen in the roots accompanied high concentrations and high rates of absorption of NH_4-N, it is apparent that the pH range which favored the most rapid rate of absorption of NH_4-N also favored the most rapid assimilation of NH_4-N.

As a result of the experimental conditions prevailing, it was not possible to trace in considerable detail the course of assimilation of the two forms of nitrogen in the tops of plants grown in solutions of different pH.

REFERENCES

(1) BEAUMONT, A. B. 1932 The toxicity of ammonium compounds for tobacco. *Proc. 2nd Internatl. Cong. Soil Sci.* 4: 65–78.

(2) CHIBNALL, A. C., AND MILLER, E. J. 1931 Some observations on the distribution of nitrogen in plant extracts that contain a high proportion of nitrate nitrogen. *Jour. Biol. Chem.* 90: 189–196.

(3) CLARK, H. E., AND SHIVE, J. W. 1934 The influence of the pH of a culture solution on the rates of absorption of ammonium and nitrate nitrogen by the tomato plant. *Soil Sci.* 37: 203–225.

(4) DAVIDSON, O. W., CLARK, H. E., AND SHIVE, J. W. A comparison of two methods of preparing aqueous extracts of soluble nitrogen from plant tissues. In press, *Plant Physiol.*

(5) DIKUSSAR, I. G. 1930 Die Wirkung des Ammoniumsulfats und des Saltpeters auf die Entwicklung von Zuckerrübe und Mais in Abhängigkeit von der chemischen Zusammensetzung der Nährlösung. *Landw. Jahrb.* 72: 79–104.

(6) ECKERSON, S. H. 1932 Conditions affecting nitrate reduction in plants. *Contrib. Boyce-Thompson Instit.* 4: 119–130.

(7) HUTCHINSON, H. B., AND MILLER, N. H. J. 1909 Direct assimilation of ammonium salts by plants. *Jour. Agr. Sci.* 3: 179–193.

(8) KRAUS, E. J., AND KRAYBILL, H. R. 1918 Vegetation and reproduction with special reference to the tomato. Oreg. Agr. Exp. Sta. Bul. 149.

(9) MAZÉ, P. 1900 Recherches sur l'influence de l'azote nitrique et de l'azote ammoniacal sur le dévéloppement du mais. *Ann. Inst. Pasteur* 14: 26–45.

(10) MEVIUS, W., AND ENGEL, H. 1929 Die Wirkung der Ammoniumsalze in ihrer Abhängigkeit von der Wasserstoffionenkonzentration II. *Planta* 9: 1–83.

(11) NIGHTINGALE, G. T., ROBBINS, W. R., AND SCHERMERHORN, L. G. 1927 Freezing as a method of preserving plant tissue for the determination of nitrogenous fractions. N. J. Agr. Exp. Sta. Bul. 448.

(12) NIGHTINGALE, G. T., SCHERMERHORN, L. G., AND ROBBINS, W. R. 1928 The growth status of the tomato as correlated with organic nitrogen and carbohydrates in roots, stems, and leaves. N. J. Agr. Exp. Sta. Bul. 461.

(13) OSBORNE, T. B., AND HARRIS, I. F. 1903 Nitrogen in protein bodies. *Jour. Amer. Chem. Soc.* 25: 323–353.

(14) PIRSCHLE, K. 1931 Nitrate und Ammonsalze als Stickstoffquellen für höhere Pflanzen bei konstanter Wasserstoffionenkonzentration. *Planta* 14: 583–676.

(15) PLIMMER, R. H. A. 1925 Action of nitrous acid upon amides and other "amino" compounds. *Jour. Chem. Soc.* [London] 127: 2651–2659.

(16) PRIANISCHNIKOW, D. N. 1926 Ammoniak, Nitrate, und Nitrite als Stickstoffquellen für höhere Pflanzen. *Ergeb. Biol.* 1: 407–46.

(17) PRIANISCHNIKOW, D. N. 1929 Zur Frage nach der Ammoniakernährung von höheren Pflanzen. *Biochem. Ztschr.* 207: 341–349.

(18) RANKER, E. R. 1927 A modification of the salicylic-thiosulfate method suitable for the determination of total N in plants, plant solutions, and soil extracts. *Jour. Assoc. Off. Agr. Chem.* 10: 230–251.

(19) SESSIONS, A. C., AND SHIVE, J. W. 1928 A method for the determination of inorganic nitrogen in plant extracts. *Plant Physiol.* 3: 499–511.

(20) SESSIONS, A. C., AND SHIVE, J. W. 1933 The effect of culture solutions on growth and nitrogenous fractions of oat plants at different stages of their development. *Soil Sci.* 35: 355–374.

(21) TIEDJENS, V. A., AND ROBBINS, W. R. 1931 The use of ammonia and nitrate nitrogen by certain crop plants. N. J. Agr. Exp. Sta. Bul. 526.

(22) VAN SLYKE, D. D. 1911 A method for quantitative determination of aliphatic amino groups. *Jour. Biol. Chem.* 9: 185–204.

(23) VICKERY, H. B. 1927 The basic nitrogen of plant extracts. *Plant Physiol.* 2: 303–311.

(24) VICKERY, H. B., AND PUCHER, G. W. 1931 A source of error in the determination of amide nitrogen in plant extracts. *Jour. Biol. Chem.* 90: 179–188.

A METHOD FOR DETERMINING THE CAPACITY OF A SOIL TO FIX PHOSPHORUS IN DIFFICULTLY AVAILABLE FORM[1]

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It has long been known (1, 3) that when soluble phosphates are applied to soils, they change to less soluble forms, the availability of which varies. If the fixed phosphorus is combined with calcium, it is considered readily available, but if with iron or aluminum, more or less difficultly available.[3] Since soils vary greatly in fixing power, it is important to be able to classify them as to their capacity to fix phosphorus in difficultly available forms. This may be done by treating a moist soil with soluble phosphate, allowing it to stand for a given length of time under moist conditions, and then determining the phosphorus still readily available. Ford (1) has described a laboratory method in which the soil and soluble phosphate are evaporated to dryness at 30°C. This procedure hastens the reaction and greatly reduces the time. Using Ford's method as a basis and starting point, the writer proceeded to perfect the procedure so as to make it shorter and more reliable. The method outlined in this paper is the result of this work.

EXPERIMENTAL

The effect of time and temperature. The work of Scarseth (5), as well as work in this laboratory, and field experience, indicate that time is an important factor in the fixation of phosphates in soils, although much of the fixation in a moist soil takes place almost immediately or within a few hours after the application of a soluble phosphate. After this initial fixation, the change is much slower, and the balance between the readily available and the fixed phosphorus approaches an equilibrium, but with a tendency toward an increase in the fixed phosphorus. Under normal field conditions, equilibrium is practically established in from 1 to 12 months.

[1] Contribution from the department of soils, University of Wisconsin, Madison, Wisconsin. Published with the permission of the director of the Wisconsin Agricultural Experiment Station.

[2] The writer is appreciative of the kindly coöperation of Prof. E. Truog in connection with this study.

[3] The term "fixation" has been used to refer to the change of phosphorus in the soil to forms only slightly soluble in water, and, also, in a more restricted sense, to apply only to the change of phosphorus to the difficultly available form. The latter meaning will be generally understood in this paper.

The effect of time on the fixation of phosphates in the difficultly available form was determined in Miami silt loam and Superior clay from Wisconsin, Memphis silt loam (Mayfield) from Kentucky, and a lateritic soil from the Waipio Substation, Experiment Station Hawaiian Sugar Planters' Association, Hawaii. To each soil was added 400 p.p.m. of phosphorus as monocalcium phosphate dissolved in enough water to make the soil up to optimum moisture. The soils were held at this moisture content and room temperature, and the readily available phospsorus was determined by the Truog method (6, 7) after 2, 10, 20, 40, and 80 days.

It was found that some fixation occurred during the extraction process, and to correct for this error a factor was employed. On the basis of a soil's capacity

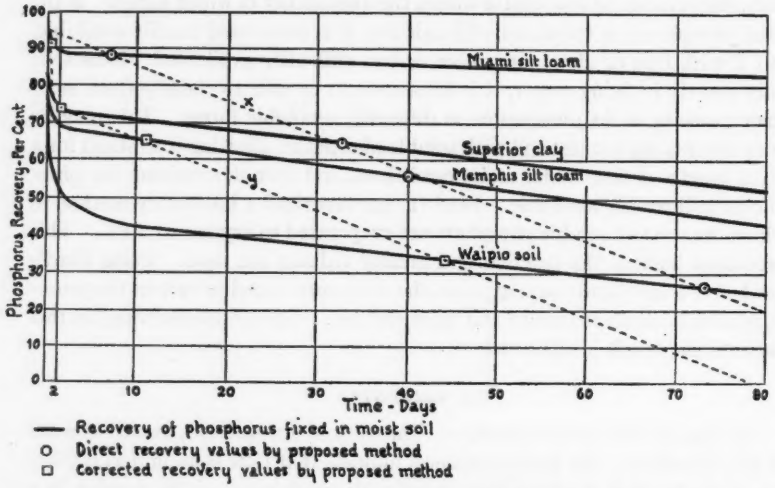

FIG. 1. THE RECOVERY OF APPLIED PHOSPHORUS FIXED IN MOIST SOILS IN READILY AVAILABLE FORM, AND THE RELATION OF THE DIRECT AND CORRECTED RECOVERY VALUES OF THE PROPOSED METHOD TO THESE DATA

to fix 100 per cent of the applied phosphorus in difficultly available form, the factor 1.375[4] was used, and the direct recovery values were multiplied by the proper correction factor When this correction factor is assumed to follow a straight line, varying from 1.0 at zero fixation to 1.375 at 100 per cent fixation, the increment of recovery is a parabolic function and follows the equation, $y^2 = 2px$, in which $p = 135$. On this basis the fixation curves for the four soils mentioned were determined and are shown in figure 1.

These curves show that the most pronounced fixation takes place within a

[4] This factor was found experimentally by adding to the soil in the extracting solution 400 p.p.m. of phosphorus as monocalcium phosphate, and then determining the amount of this phosphorus fixed by the soil during a 30-minute period of extraction.

few hours, and that after a transition period, varying from 2 to 10 days, the fixation takes the form of practically a straight line with a tendency to be somewhat asymptotic, and which slowly approaches the zero line of recovery. It was found that heat could, in part, be substituted for time, and values obtained which would show the relative capacities of soils to fix phosphorus in the difficultly available form, and, at the same time, would be fair measures of what would take place under normal field conditions. This was accomplished by refluxing the soil in the phosphate solution at 100°C. for 45 minutes. It was also found that if the soil and the phosphate solution were slowly boiled to dryness, the result was the same as when they were refluxed. From these facts, the following method for determining the capacity of a soil to fix phosphorus in the difficultly available form was developed.

The method. One-half gram of 40-mesh soil is placed in a 500-cc. Erlenmeyer flask, and to it are added 2 cc. of a solution of monocalcium phosphate containing 0.1 mgm. of phosphorus per cubic centimeter, and 50 cc. of water. This is an application of 400 p.p.m. of phosphorus. Phosphoric acid or any soluble phosphate may be used, but the monocalcium phosphate is more comparable to the common superphosphate used in the field. The flask is then heated, the contents are boiled gently almost to dryness, and the process is completed on a steam plate or steam bath. The boiling should not be too vigorous, but rapid enough to complete the evaporation in about 45 minutes. In this way superheating is prevented. Into a similar flask is placed a half-gram sample of the untreated soil, and then to each of the two flasks is added 200 cc. of 0.002 *N* sulfuric acid buffered to pH 3. The two are shaken for 30 minutes, filtered, and the phosphorus is determined by the method of Truog and Meyer (6, 7). The amount of phosphorus extracted from the treated soil minus the amount from the untreated soil gives the amount of applied phosphorus recovered. This latter amount, subtracted from the applied phosphorus, gives the phosphorus fixed in difficultly available form. An example of the calculation for Carrington silt loam follows:

Soil + 400 p.p.m. phosphorus gave on extraction, 320 p.p.m. available phosphorus
Soil, untreated, gave on extraction, 20 p.p.m. available phosphorus
Applied phosphorus recovered, 300 p.p.m. available phosphorus

$\frac{300}{400} \times 100 = 75$ per cent, applied phosphorus recovered in readily available form.

On this basis, 25 per cent of the applied phosphorus was fixed in difficultly available form. If the recovery is to be corrected for the fixation during extraction, the 75 per cent is multiplied by 1.09 (factor for 25 per cent fixation) which results in a corrected recovery value of 81.7 per cent.

The fixation and recovery values by this method for the four soils referred to in figure 1 were determined and are given in table 1. If the direct recovery values from this table are inserted in the proper places in figure 1, the line x is established, and if the corrected recovery values are used, the line y. The points at which these lines intersect the fixation curves for the different soils

indicate the time at which the fixation of applied soluble phosphorus in a normally moist soil would be equal to the values obtained by the method as outlined. It appears from these data that the direct recovery values and their corresponding fixation values are a little nearer to the fixation values obtained under normal conditions in the field when the length of the growing season is considered than are the corrected values.

TABLE 1

The fixation in difficulty available form, as measured by laboratory method, and the recovery of soluble phosphate applied to the four soils referred to in figure 1

SOIL	APPLIED PHOSPHORUS FIXED (DIRECT)	APPLIED PHOSPHORUS RECOVERED IN READILY AVAILABLE FORM	
		Direct	Corrected
	per cent	*per cent*	*per cent*
Miami silt loam	13.5	86.5	90.8
Superior clay	35.5	64.5	73.6
Memphis silt loam (Mayfield)	44.0	56.0	65.0
Waipio soil (Lateritic)	74.0	26.0	33.2

TABLE 2

The pH values, readily available phosphorus, and the phosphorus fixing power of 14 soils

SOIL	pH VALUE (HYDROGEN ELECTRODE)	READILY AVAILABLE NATIVE PHOSPHORUS	FIXING POWER	
			Dried at 50°C.	Dried at 100°C.
		p.p.m.	*per cent*	*per cent*
1. Placenta loam (California)	7.73	72	0.5	11.7
2. Makiki (vir.) (Hawaii)	7.41	690	45.0	62.5
3. Opaeula 6 (Waialua-Hawaii)	7.11	12	....	60.0
4. Palouse silt loam (Washington)	6.71	162	0.5	14.3
5. Waipio (Waipio Sub-Sta. Hawaii)	6.66	88	....	70.8
6. Miami silt loam (Wisconsin)*	6.65	74	0.0	8.5
7. Kawaihapai 3 (Waialua-Hawaii)	6.49	420	10.0	30.0
8. Opaeula 18 (Waialua-Hawaii)	6.09	Trace	67.0	80.0
9. Colby silt loam (Wisconsin)	6.08	26	35.3	46.5
10. Helemano 2A (Waialua-Hawaii)	5.94	20	51.0	70.0
11. Carrington silt loam (Wisconsin)	5.67	20	20.0	25.0
12. Aiken clay adobe (California)	5.57	Trace	71.0	87.0
13. Manoa (vir.) (Manoa Sub-Sta. Hawaii)	5.40	124	90.5	100.0
14. A.H.P.C. 631 (Maui-Hawaii)	4.40	12	....	94.0

* Not the same Miami referred to in table 1.

Results by this method were also compared with those by a method similar to the one used by Ford (1) in which the same amount of soil and the same amounts of phosphorus and water as used in this method were placed in beakers and held at 50°C. until dry. This required about 24 hours. After this, the

samples were extracted as in the method described. Figures by both methods, together with the pH values and the readily available phosphorus contents obtained with a number of soils, are given in table 2.

DISCUSSION

The method of extraction after fixation is essentially that of Truog (6), except that a ratio of soil to solution of 1 to 400 was used. This higher ratio of solvent aids materially in maintaining the pH of the extracting solution at more nearly its original value of 3, and, unless the soil contains appreciable amounts of calcium carbonate, this can be done with only a slight rise. Since the fixation in highly calcareous soils will be generally in the form of calcium phosphate (3), a form which is readily available, this method may be used to best advantage with soils containing not more than a small amount of calcium carbonate. None of the soils listed in table 2 contained appreciable amounts of calcium carbonate.

The figures in table 2 indicate that the amounts of applied phosphorus changed to the difficultly available form may vary from practically nothing to all of the phosphorus applied. This will hold true only up to a certain amount of applied phosphorus. Using 1 per cent citric acid as the extracting solution, McGeorge (4) found that above a certain amount of applied phosphorus there was a dropping off of the percentage fixed, although there was a steady increase in the total amount of phosphorus fixed. Four hundred parts per million does not approach this amount and seems to be a very convenient and satisfactory amount to use.

The higher temperature of evaporation gives from 8 to 18 per cent higher fixation values than the lower temperature, and indicates some fixation with all soils, which seems logical, because a soil like the Miami silt loam should contain some material capable of fixing phosphorus in difficultly available form. Again, some soils should be capable of fixing all of the 400 p.p.m. of applied phosphorus, but none of the soils show this at the lower temperature. On the whole, the higher temperature gives results more nearly in accord with the fixation curves in figure 1, and with what might be expected from longer contact under field conditions. At the same time this method is more convenient because of the shorter time involved.

Of the soils listed in table 2, the laterites from Hawaii and the Aiken clay adobe from California have the greatest capacity for fixing phosphorus in the difficultly available form, apparently, because of the large amount of hydrated ferric oxide which they contain. The Miami silt loam used is typical of a low fixing soil. It not only contains very little active iron or aluminum, but at the same time its pH value is high enough so that it is well supplied with exchangeable calcium, thus holding the applied phosphorus as calcium phosphate.

A method involving water extraction instead of that by a weak acid has been recently proposed by Hance (2), but obviously such a method cannot be used for the estimation of the capacity of a soil to fix phosphorus in the difficultly

available form. Most soils tend to change soluble phosphate to a form relatively insoluble in water, but this may be the readily available calcium phosphate. Basic soils with little or no active iron or aluminum will tend to fix practically all of the applied soluble phosphate in this form.

In some virgin soils containing a relatively large amount of phosphorus associated with organic matter, there is a tendency for the boiling to bring about hydrolysis of a part of this phosphorus and allow it to be fixed in the difficultly available form. However, because of the tendency of each soil to establish its own equilibrium between the readily available and fixed phosphorus, there is a tendency for any phosphorus fixed from this organic source to be balanced by an equal amount of applied phosphorus left readily available. For this reason perhaps, no soil has been found to give an apparent fixation of more than 100 per cent of the applied phosphorus. In most cultivated soils any error from this source has been found to be negligible.

The outlines of this method were furnished A. R. Midgley of the Vermont Experiment Station and were used by Weiser (8) of that station in a very recent work in which he reports obtaining very satisfactory results with Vermont soils.

SUMMARY

A method is outlined in which 0.5 gm. of soil is treated with 0.2 mgm. (400 p.p.m.) of phosphorus as monocalcium phosphate in solution in 50 cc. of water, and the suspension boiled to dryness. The readily available phosphorus is then determined by means of 0.002 *N* sulfuric acid buffered to pH 3. This amount, subtracted from the sum of what was added and present in the soil before treatment, gives the amount fixed, which makes it possible to calculate the capacity of the soil to fix phosphorus in difficultly available form.

Results by this method compare favorably with results obtained under field conditions. The time required in the field for a soil to attain the fixation percentage indicated by this method becomes proportionately greater as the capacity of the soil for fixation increases.

REFERENCES

(1) FORD, M. C. 1933 The nature of phosphate fixation in soils. *Jour. Amer. Soc. Agron.* 25: 134–144.

(2) HANCE, F. E. 1932 A new field kit for the rapid measurement of soil phosphate fixation. *Hawaii Sugar Planters' Assoc., Rep. Exp. Sta. Com.* 86–87.

(3) HECK, A. FLOYD 1934 Phosphate fixation and penetration in soils. *Soil Sci.* 37: 343–355.

(4) MCGEORGE, W. T. 1923 A study of the phosphates in the island sugar lands. Hawaii. Sugar Planters' Assoc., Exp. Sta. Agr. and Chem. Bul. 47.

(5) SCARSETH, G. D. 1932 Morphological, greenhouse, and chemical studies of the Black Belt soils of Alabama. Ala. Agr. Exp. Sta. Bul. 237.

(6) TRUOG, E. 1930 The determination of the readily available phosphorus of soils. *Jour. Amer. Soc. Agron.* 22: 874–882.

(7) TRUOG, E., AND MEYER, A. H. 1929 Improvements in the Deniges colorimetric method for phosphorus and arsenic. *Indus. and Engin. Chem. Anal. Ed.* 1: 136–139.

(8) WEISER, V. L. 1933 Fixation and penetration of phosphates in Vermont soils. Vt. Agr. Exp. Sta. Bul. 356.

A COMPARISON OF SUPERPHOSPHATE AND RAW ROCK PHOSPHATE ON DIFFERENT TYPES OF SOIL[1]

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The loam and sandy loam soils of New Jersey are generally fairly constant in phosphoric acid content. In most cases the loams contain about 0.10 to 0.14 per cent phosphoric acid. Eleven samples representing different types of loam soils from the Belvidere area average 0.132 per cent phosphoric acid (2). There are, however, some exceptions to this general statement. Colts Neck loam contains an exceptionally high percentage, ranging from about 0.7 to more than 1 per cent phosphoric acid. Three samples of this soil from Monmouth County averaged 0.94 per cent, with the subsoil containing as much as, and sometimes more than, the topsoil (1). Sassafras and Portsmouth loams may contain as much as 0.20 per cent phosphoric acid. Loams which are derived from limestone formations are likely to contain a slightly higher percentage than are those derived from igneous rocks, shales, and slates.

During the past 25 years this question of the comparative availability of superphosphate and rock phosphate has been carefully studied by a number of the experiment stations in this country and abroad. In 1918, Waggaman and Wagner (12) made a careful analysis of the experimental work with ground raw rock phosphate as a fertilizer. Among others who have made contributions to the subject may be mentioned Brooks (4), Hartwell and Damon (6), McGeorge (8), Mooers (9), Truog (11), Williams, C. B. (16), and Wiancko and Conner (15).

With the exception of the work done at the Hawaiian experiment station, none of these workers has compared the two phosphates on a soil which contains as high a percentage of phosphoric acid as the Colts Neck loam. The question naturally arose, therefore, as to whether crops grown on Colts Neck loam and on other soils which contain an unusual amount of native phosphates would respond to treatments of soluble phosphates or ground rock phosphate. For the purpose of studying this problem three types of soil were obtained for experimental work in cylinders[2] located at the experiment station. The three soils were a Colts Neck loam from Monmouth County, and Sassafras and Portsmouth loams from Middlesex County. The Colts Neck loam was from

[1] Journal Series paper of the New Jersey Agricultural Experiment Station, department of soil chemistry and bacteriology.

[2] The type of cylinder that has been used at this station for the past 35 years.

good land where clover was growing and was only slightly acid, pH 6.5, with a lime requirement (CaO by Veitch method) of 100 pounds to the acre. It contained 0.77 per cent total phosphoric acid. The Sassafras loam was taken from an abandoned field in the vicinity of Dayton and was poorer than the average soil of this type. It was distinctly acid, having a pH of 6.2 and a lime requirement of 600 pounds calcium oxide to the acre. It contained 0.1 per cent total phosphoric acid. The Portsmouth loam was taken from a swampy area in the vicinity of Dayton and had not been under cultivation. It was strongly acid, having a pH of 5.2 and a lime requirement of 4,000 pounds calcium oxide to the acre. It contained 0.2 per cent total phosphoric acid. A partial chemical analysis of these soils is herewith given (3).

	Colts Neck loam *per cent*	Sassafras loam *per cent*	Portsmouth loam *per cent*
N	0.126	0.053	0.451
P_2O_5	0.772	0.108	0.202
K_2O	1.660	0.950	1.341
CaO	0.660		
MgO	0.750		
Fe_2O_3	25.180		
Al_2O_3	5.840		
Organic carbon		1.380	5.710
pH	6.5	6.2	5.2
Lime requirement (Veitch)	100	600	4000

PLAN OF TREATMENT

The plan of treatment provides for applications of superphosphate to give 0.5, 1.0, 2.5, and 5.0 gm. of phosphoric acid per cylinder on one section and equivalent amounts of ground phosphate rock (ground as for the preparation of superphosphate) on another section. The superphosphate treatments are equivalent to 100, 200, 500, and 1,000 pounds to the acre. In addition to the phosphate, all cylinders received 10 gm. nitrate of soda, or the equivalent in nitrate of soda and sulfate of ammonia, and 10 gm. of muriate of potash, these amounts being equivalent to 320 pounds of nitrate of soda and 320 pounds of muriate of potash to the acre. All fertilizers were applied annually. To one-half of the cylinders that received the ground phosphate rock, calcium sulfate was applied in amounts equivalent to the amount of calcium sulfate contained in the superphosphate used on the other section.

A limed and an unlimed series was provided for each type of soil.

The soils were collected and placed in the cylinders in the fall of 1922. Fertilizers and lime were applied in accordance with the plan outlined in the foregoing, and rye was planted on the Sassafras loam and the Portsmouth loam. The Colts Neck loam was placed in the cylinders too late for the planting of rye.

Colts Neck Loam

Limed section.[3] Barley and soybeans were grown on this soil in 1923; potatoes in 1924, 1925, 1926, and 1927; and grain and forage crops in 1928 to 1932 inclusive. [The results for the potatoes have been published (3).] Crop yields for the years 1923, 1927, 1928, 1929, 1930, 1931, and 1932 for the limed section of the Colts Neck loam are shown in table 1. It will be noted that two crops were grown in 1923, 1927, and 1930.

TABLE 1

Yields of dry matter in a comparison of superphosphate and raw rock phosphate on Colts Neck loam—limed section—1923–1932

SPECIAL TREATMENT	BARLEY 1923		SOYBEAN HAY 1923	BUCKWHEAT 1927	CORN FORAGE 1928	OATS 1929		RAPE 1930	SOYBEAN HAY 1930	BARLEY 1931		BARLEY 1932		ANNUAL AVERAGE		
	Grain	Straw				Grain	Straw			Grain	Straw	Grain	Straw	Grain	Straw	Hay, etc.
gm. per cylinder	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*
Superphosphate Section																
Check	47	60	82	28	343	53	96	90	116	38	68	23	46	40	68	165
0.5 gm. P_2O_5*	57	65	93	52	360	51	97	100	134	43	76	20	40	43	70	185
1.0 gm. P_2O_5	62	68	98	58	423	59	98	101	147	47	90	37	63	51	80	207
2.5 gm. P_2O_5	62	71	92	57	412	50	108	114	150	52	94	32	66	49	85	206
5.0 gm. P_2O_5	63	70	85	60	437	57	102	105	144	55	96	46	87	55	89	208
Average of 4 treatments	61	69	92	57	408	54	101	105	144	49	89	34	64	50	81	202
Raw Rock Phosphate Section																
Check	57	64	87	51	413	60	92	90	138	47	78	46	74	53	77	195
0.5 gm. P_2O_5	54	64	79	52	364	56	97	90	116	47	85	39	71	49	79	175
1.0 gm. P_2O_5	56	65	77	46	360	56	93	87	101	45	84	48	75	51	79	168
2.5 gm. P_2O_5	55	66	68	40	353	54	91	102	113	38	80	43	74	48	78	169
5.0 gm. P_2O_5	59	63	80	51	377	51	107	102	102	43	87	45	73	50	83	178
Average of 4 treatments	56	65	76	47	364	54	97	95	108	43	84	44	73	50	80	173

* 0.5 gm. per cylinder is equal to 100 pounds superphosphate per acre.

The averages in table 1 show that the superphosphate treatment gave some increase over the check. For example, the average increase of hay and forage with 0.5 gm. P_2O_5 (100 pounds superphosphate to the acre) is 20 gm., which is equivalent to 640 pounds to the acre. For the hay and forage the increase with 200 pounds of superphosphate to the acre is about twice as much as with 100 pounds. The 500 and 1,000-pound applications did not give much increase over the 200-pound application.

[3] In July, 1923, the pH of the limed soil was 7.1 and of the unlimed soil 6.65; the corresponding figures for July, 1932, were 7.17 and 6.18.

For the ground rock section the phosphate treatments show little increase over the check. Indeed, in a number of cases the yields with the phosphate rock are somewhat less than the yields on the check cylinders. This would indicate that the phosphorus of the ground rock is no more available than the natural phosphate of the soil. Such increases as are noted occur with the soybean hay and corn forage rather than with the grain. The average yields for this section are in most cases slightly less than the averages for the superphosphate section.

TABLE 2

Yields of dry matter in a comparison of superphosphate and raw rock phosphate on Colts Neck loam—unlimed section—1923–1932

SPECIAL TREATMENT	BARLEY 1923		SOYBEAN HAY 1923	BUCKWHEAT 1927	CORN FORAGE 1928	OATS 1929		RAPE 1930	SOYBEAN HAY 1930	BARLEY 1931		BARLEY 1932	ANNUAL AVERAGE		
	Grain	Straw				Grain	Straw			Grain	Straw	Grain and Straw	Grain	Straw	Hay, etc.
gm. per cylinder	*gm.*	*gm*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*	*gm.*
Superphosphate Section															
Check	57	61	72	50	345	57	88	79	97	39	65	61†	51	71	141
0.5 gm. P_2O_5*	55	63	74	59	368	52	89	87	108	44	73	80†	50	75	155
1.0 gm. P_2O_5	56	72	84	44	419	52	87	69	119	44	77	71	51	79	161
2.0 gm. P_2O_5	61	73	79	51	417	50	92	103	131	39	74	81†	50	80	172
5.0 gm. P_2O_5	62	73	70	47	430	58	88	111	113	46	89	101	55	83	174
Average of 4 treatments	59	70	77	50	409	53	89	93	118	43	78	83	52	79	166
Rock Phosphate Section															
Check	54	64	71	54	381	46	95	72	99	42	84	83	47	81	152
0.5 gm. P_2O_5	60	69	76	50	341	47	93	88	110	49	82	75	52	81	148
1.0 gm. P_2O_5	55	68	65	45	360	52	87	98	93	42	77	109†	50	77	154
2.5 gm. P_2O_5	56	65	67	42	340	52	89	101	105	46	83	99	51	79	151
5.0 gm. P_2O_5	46	62	57	54	319	54	90	93	92	40	87	108	47	80	145
Average of 4 treatments	54	66	66	48	340	51	90	95	100	44	82	98	50	79	150

* 0.5 gm. per cylinder is equal to 100 pounds superphosphate per acre.

† One cylinder only.

Unlimed section. The dry weights for the unlimed section of the Colts Neck loam are given in table 2, which shows that the yields on this section were somewhat lower than the yields on the limed section, notwithstanding the fact that the soil was only moderately acid.

In a number of instances superphosphate has given some increase in yield of dry matter over the check cylinders, but in most cases this increase would not justify the application of 200 or even 100 pounds of superphosphate to the

acre. It is probable that only in the case of the corn forage would the increase justify the use of 500 pounds to the acre.

For the rock phosphate section the check cylinders frequently gave yields equal to, or greater than, the yields on the treated cylinders. The averages for this section do not indicate any value for the rock phosphate, either in small or large amounts.

TABLE 3

Yields of dry matter in a comparison of superphosphate and raw rock phosphate on Sassafras loam—limed section—1923–1932

SPECIAL TREATMENT	RYE 1923		SOYBEAN HAY 1923	CORN FORAGE 1928	OATS 1929	RYE 1930	SOYBEAN HAY 1930	BARLEY 1931		BARLEY 1932		ANNUAL AVERAGE		
	Grain	Straw						Grain	Straw	Grain	Straw	Grain	Straw	Hay, etc.
gm. per cylinder	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.
Superphosphate Section														
Check	25	63	74	399	97	49	130	30	62	36	52	30	59	187
0.5 gm. P_2O_5*	29	82	60	417	103	60	127	35	69	20	40	28	64	192
1.0 gm. P_2O_5	28	76	62	433	102	59	128	31	78	29	57	29	71	196
2.5 gm. P_2O_5	24	76	58	509	106	61	143	33	89	34	71	30	79	219
5.0 gm. P_2O_5	24	75	66	507	105	66	146	37	93	37	79	33	82	222
Average of 4 treatments	26	77	62	467	104	62	136	34	82	30	62	30	74	207
Raw Rock Phosphate Section														
Check	20	65	68	386	91	56	130	35	70	33	65	30	67	183
0.5 gm. P_2O_5	23	67	71	375	103	56	135	37	73	35	62	32	67	185
1.0 gm. P_2O_5	24	66	74	413	103	46	138	34	67	33	54	30	63	194
2.5 gm. P_2O_5	20	64	65	377	113	53	129	32	69	31	40	28	58	184
5.0 gm. P_2O_5	19	67	70	352	96	45	127	33	67	29	51	27	62	172
Average of 4 treatments	22	66	70	379	104	50	132	34	69	32	52	29	63	184

* 0.5 gm. per cylinder is equal to 100 pounds superphosphate per acre.

SASSAFRAS LOAM

Limed section. The fertilizer and lime treatments and the crops grown were the same for this soil as for the Colts Neck loam. The yields for the limed section are shown in table 3. A study of the averages for the superphosphate section shows, in most cases, only slight increases for the phosphate treatments as compared with the check. Generally, the increases in hay, straw, and forage were greater than the increases in grain. The average increase in hay and forage for the 500-pound application lacked only 3 gm. per cylinder of being as much as the increase with the 1,000-pound application.

The yields for the ground rock section are generally slightly less than for the superphosphate section, and they likewise show a smaller increase over the check. Indeed, in the majority of cases the yields are practically as high for the check cylinders as for those that received the heaviest phosphoric acid treatment. It appears, therefore, that even on this soil, where a deficiency of available phosphoric acid would be expected, there was very little response to the phosphate treatment.

Unlimed section. The yields of rye and soybeans in 1923 and of corn forage in 1928 on this soil were very nearly as good as corresponding yields on the

TABLE 4

Yields of dry matter in a comparison of superphosphate and raw rock phosphate on Portsmouth loam—limed section—1923, 1930, 1931, 1932

SPECIAL TREATMENT	RYE 1923		SOYBEAN HAY 1923	RYE 1930	SOYBEAN HAY 1930	BARLEY 1931		BARLEY 1932		ANNUAL AVERAGE		
	Grain	Straw				Grain	Straw	Grain	Straw	Grain	Straw	Hay, etc.
gm. per cylinder	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.	gm.
Superphosphate Section												
Check	36	90	78	114	140	30	62	28	53	31	68	166
0.5 gm. P_2O_5*	50	121	75	104	151	41	76	29	50	40	82	165
1.0 gm. P_2O_5	32	84	87	93	163	39	78	32	50	34	71	172
2.5 gm. P_2O_5	29	88	84	100	160	42	86	38	66	36	80	172
5.0 gm. P_2O_5	33	102	89	116	146	43	90	53	65	43	86	175
Average of 4 treatments	36	99	84	103	155	41	83	38	58	38	80	171
Raw Rock Phosphate Section												
Check	36	99	81	110	150	38	74	37	53	37	75	171
0.5 gm. P_2O_5	27	83	87	90	143	39	71	15	38	27	64	160
1.0 gm. P_2O_5	27	88	78	85	153	39	75	42	55	36	73	158
2.5 gm. P_2O_5	42	109	78	90	167	41	88	38	55	40	84	168
5.0 gm. P_2O_5	35	105	81	65	161	44	87	46	64	42	85	154
Average of 4 treatments	33	96	81	83	156	41	80	35	53	36	77	160

* 0.5 gm. per cylinder is equal to 100 pounds superphosphate per acre.

limed section, but except for the corn forage neither the superphosphate nor the rock phosphate had much effect on the yield of dry matter. By 1929 the soil had become so acid that yields were very much reduced. The rye and soybeans in 1930 were a failure, the barley crop in 1931 was scarcely worth harvesting, and no crop was planted in 1932. By this time the soil was so acid—pH 5.0 to 5.3—that even the 1,000-pound application of phosphate had little effect.

The yields of dry matter from this section are so irregular that their inclusion in the paper is not justified.

PORTSMOUTH LOAM

Limed section. The plan of treatment was the same as for the Colts Neck and Sassafras soils. However, potatoes were grown on this soil for 2 years (1928 and 1929) after the growing of potatoes had been discontinued on the other two soils. The yields were irregular and are not recorded here.

The dry weights of the other crops for the limed section are shown in table 4. An examination of the table brings out the fact that there is very little difference between the yields from the check plots and those from the phosphate treated plots. There is also little difference between the yields from the superphosphate plots and the rock phosphate plots. Thus it would appear that grain crops and soybeans on Portsmouth loam, with a high percentage of organic matter and phosphoric acid, do not respond to phosphate treatment.

Unlimed section. The yields on the unlimed section of this soil were very irregular and decreased rapidly as the soil became more acid, and therefore have no value for publication. The pH of the soil in May, 1932, when no crop was growing, varied between 4.9 and 5.3.

GENERAL DISCUSSION

On well-limed Colts Neck loam soil, which contains an exceptionally high percentage of phosphoric acid, superphosphate gave some increase over the check when used for general farm crops, but in a number of cases the application of 200 pounds to the acre or even 100 pounds of the superphosphate did not give a *profitable* increase.

If one may judge by the yields of dry matter, the rock phosphate, which was applied in amounts equivalent to the superphosphate, was little, if any, more available than the native soil phosphates.

Neither of the phosphates was definitely effective on the unlimed section of this soil.

On the limed Sassafras loam soil with a percentage of phosphoric acid about normal, most of the crops showed some response to the superphosphate treatment, but practically no response to the rock phosphate.

The soil of the unlimed series of the Sassafras loam was too acid to grow good crops, either with or without phosphate treatment.

Applications of superphosphate on limed Portsmouth loam, which also contains a rather high percentage of phosphoric acid, gave very little increase over the check. The yields on the unlimed series were so irregular as to make the data of little value.

In this connection it may be pointed out that 20 years ago Whitson and Weir (14) called attention to the fact "that soils which are acid are low in available phosphorus and will respond to an application of phosphate fertilizers."

Fudge (5) studied samples of soil from the nitrogen availability plots of the New Jersey Agricultural Experiment Station and reported that lime increased phosphate solubility on all plots except 13B. He found much more available phosphoric acid in the soil from the limed section of these plots than from the unlimed section. In further commenting on his studies of these soils he says:

Although the normal phosphates of iron and aluminum, as such, are relatively available to plants, they are very easily hydrolyzed, forming relatively unavailable basic phosphates of iron and aluminum. When lime is applied to such soils, however, the acidity is greatly decreased, and the calcium of the lime replaces much of the hydrogen of the exchange complex and furnishes calcium for the formation of the relatively available calcium phosphate.

Lyon and Buckman (7), discussing the use of soluble phosphates, say:

When the soil is acid and, therefore, lacking in effective calcium, the phosphates react with the active aluminum and iron, forming very insoluble and unavailable calcium-iron-aluminum phosphates. For this reason plenty of calcium should be present in the soil when superphosphate is used in order to insure the full effectiveness of the fertilizer. Because of the precipitation of the active aluminum, superphosphate seems to alleviate the physiological influence of soil acidity, although it may tend to increase the hydrogen ion concentration of the soil. Since lime is cheaper and more effective, it is better to reduce the acidity of the soil with this material and utilize the superphosphate as a fertilizer.

Wheeler (13) points out that liming increases the efficiency of superphosphate but decreases the efficiency of raw rock.

SUMMARY

Three types of soil—Colts Neck loam, Sassafras loam, and Portsmouth loam—were used in comparing superphosphate and rock phosphate for growing potatoes, grain, corn forage, and soybeans.

The work was carried out in cylinders of the type that has long been in use at this station.

Complete fertilizer was used in all cases except in the check cylinders, where phosphoric acid was entirely omitted.

Superphosphate was used at rates to give 100, 200, 500, and 1,000 pounds to the acre, and rock phosphate in equivalent amounts.

A series with lime and without lime was provided for each type of soil and for both phosphate treatments.

On well-limed Colts Neck loam, which is unusually rich in total phosphoric acid, grain, corn forage, and soybean hay did not, in the majority of cases, show a pronounced response to applications of superphosphate. The response was greater in the case of soybean hay and corn forage than for grain and straw. Superphosphate at the rate of 200 pounds an acre gave very nearly as great increase as 500 and 1,000 pounds.

On the rock phosphate section yields were frequently larger without phosphate treatment than with it. The averages for the grain and hay show this. This section, on the average, gave about as much grain and straw as the superphosphate section but less hay and corn forage.

On the unlimed section the yields with both superphosphate and rock phosphate are very little more than the yields on the check cylinders.

As a whole, the unlimed section gave somewhat lower yields than the limed section.

On Sassafras loam most of the crops gave a slight response to superphosphate

on the limed section. On this section they gave little or no response to the rock phosphate. On the unlimed section of this soil there was little response to either the superphosphate or rock phosphate, and by 1929 the soil had become so acid that the crops were of little value. After 1931 the unlimed section was discontinued.

The crops on the limed section of the Portsmouth loam gave but little response to the phosphate treatments.

Yields were so irregular on the unlimed section that they are not of value for record.

With conditions similar to those under which this work was carried out, it would seem to be a waste of money to use any form of phosphate on strongly acid soils or on soils such as Colts Neck loam and Portsmouth loam which are naturally well supplied with phosphorus.

Lime applied to such soils increases the availability of the natural phosphates and also the effectiveness of applied fertilizers.

REFERENCES

(1) Blair, A. W., and McLean, H. C. 1916 The chemical composition of the soils of the Freehold Area in New Jersey. N. J. Agr. Exp. Sta. Bul. 309.

(2) Blair, A. W., and McLean, H. C. 1922 The chemical composition of the soils of the Belvidere Area in New Jersey. N. J. Agr. Exp. Sta. Bul. 362.

(3) Blair, A. W., and Prince, A. L. 1927 Types of soil and the phosphate requirement of potatoes. *Proc. and Papers, 1st Internatl. Cong. Soil Sci.* 3: 477-483.

(4) Brooks, W. P. 1915 Phosphates in Massachusetts agriculture: Importance, selection, and use. Mass. Agr. Exp. Sta. Bul. 162.

(5) Fudge, J. F. 1928 The influence of various nitrogenous fertilizers on the availability of phosphate and potassium. Ala. Agr. Exp. Sta. Bul. 227.

(6) Hartwell, B. L., and Damon, S. C. 1927 The degree of response of different crops to various phosphorus carriers. R. I. Agr. Exp. Sta. Bul. 209.

(7) Lyon, L. T., and Buckman, H. O. 1929 The nature and Properties of Soils. Macmillan Co., New York.

(8) McGeorge, W. T. 1916 Phosphate fertilizers for Hawaiian soils, and their availability. Hawaii Agr. Exp. Sta. Bul. 41.

(9) Mooers, C. A. 1910 Fertility experiments in a rotation of cowpeas and wheat. Part 1, The utilization of various phosphates. Tenn. Agr. Exp. Sta. Bul. 90.

(10) Thorne, C. E. 1916 Raw phosphate rock as a fertilizer. Ohio Agr. Exp. Sta. Bul. 305.

(11) Truog, E. 1912 Factors influencing the availability of rock phosphate. Wis. Agr. Exp. Sta. Res. Bul. 20.

(12) Waggaman, W. H., and Wagner, C. R. 1918 Analysis of experimental work with ground raw rock phosphate as a fertilizer. U. S. Dept. Agr. Bul. 699.

(13) Wheeler, H. J. 1930 Ground limestone and certain phosphates. *Commercial Fert.* 40 (4): 23-25.

(14) Whitson, A. R., and Weir, W. W. 1913 Soil acidity and liming. Wis. Agr. Exp. Sta. Bul. 230.

(15) Wiancko, A. T., and Conner, S. D. 1916 Acid phosphate vs. raw rock phosphate as fertilizer. Ind. Agr. Exp. Sta. Bul. 187.

(16) Williams, C. B., Pate, W. F., Blair, E. C., Clapp, S. C., and Meacham, F. T. 1920 Relative value of acid phosphate and rock phosphate on North Carolina soils. N. C. Dept. Agr. Bul. 269, v. 41, no. 6.

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